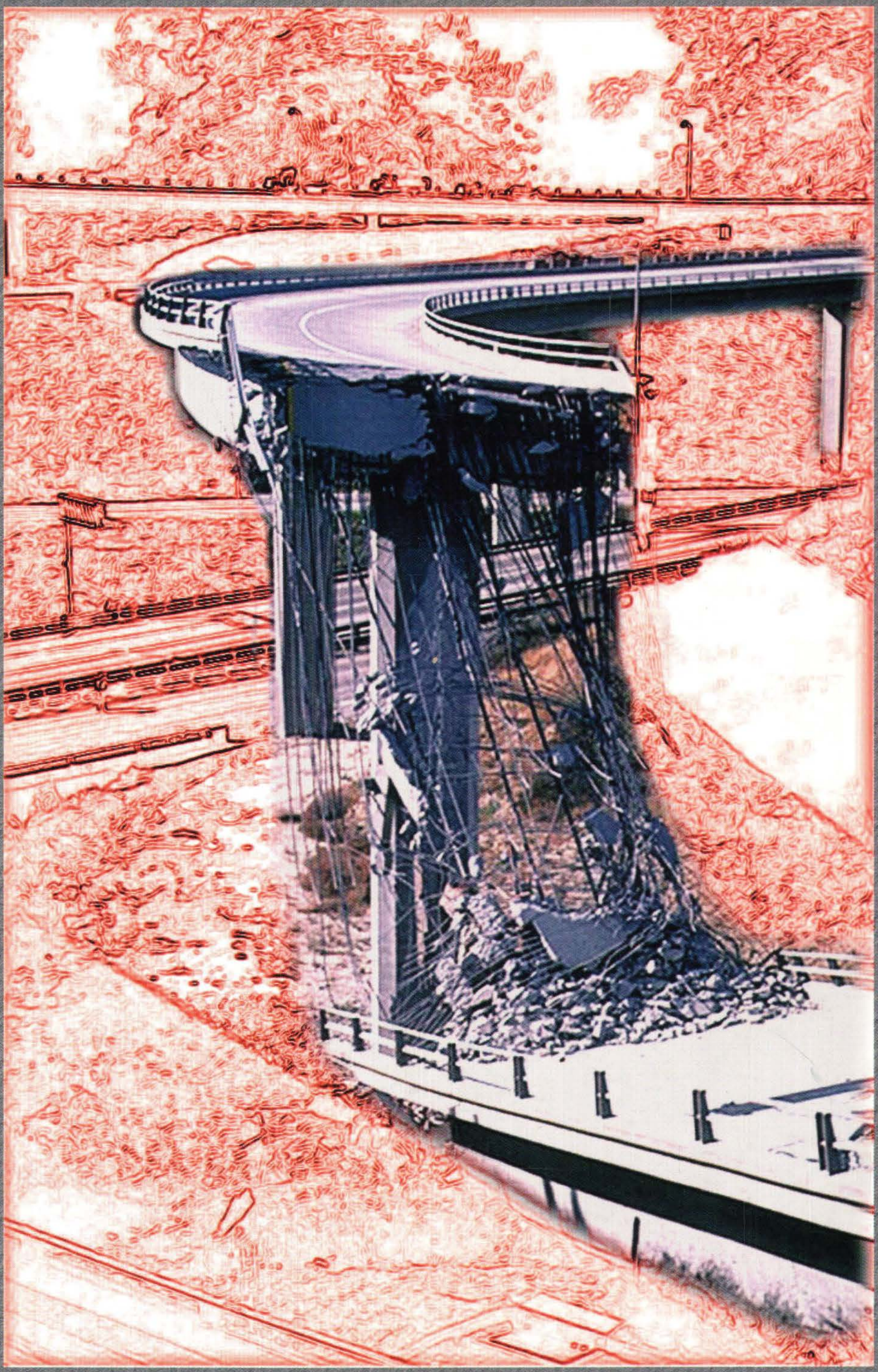
USGS Response to an Urban Earthquake



Northridge '94

This document was prepared under the guidance of the Post-Earthquake Investigations Program of the Earthquake Hazards Reduction Act. This Act requires that the four agencies participating in the National Earthquake Hazards Reduction Program (NEHRP) to carry out post-earthquake investigations programs to learn lessons that can be applied to reduce the loss of lives and property in future earthquakes. Specifically, the ***Federal Emergency Management Agency*** (FEMA), the ***National Science Foundation*** (NSF), the ***National Institute of Standards and Technology*** (NIST), and the ***U.S. Geological Survey*** (USGS) are required to organize investigations to study the implications of the earthquake in the areas of responsibility of each agency. The USGS is charged with the responsibility of organizing these investigations, and each agency is given specific roles according to that agency's mission and expertise.

This document reports specifically on the scientific work done by the U.S. Geological Survey following the Northridge, California, earthquake of January 17, 1994. This work was accomplished according to an Interagency Agreement among the four NEHRP agencies signed on March 14, 1994, that listed the post-earthquake Tasks of each agency.

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

USGS Response to an Urban Earthquake

Northridge '94

Prepared by the U.S. Geological Survey[1] *for the* Federal Emergency Management Agency (FEMA)

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Cover—This span of the interchange linking the Antelope Valley Freeway (California SH-14) and the Golden State Freeway (Interstate-5) between San Fernando and Newhall failed during strong shaking. More than any other type of damage, collapsed freeways symbolized the Northridge earthquake.

Cover photo: USGS/J. Dewey (Modified for design purposes.)

Preface

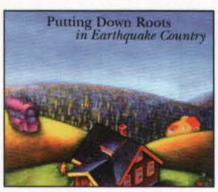
The urban centers of our Nation provide our people with seemingly unlimited employment, social, and cultural opportunities as a result of the complex interactions of a diverse population embedded in an highly-engineered environment. Catastrophic events in one or more of the natural earth systems which underlie or envelop urban environment can have radical effects on the integrity and survivability of that environment. Earthquakes have for centuries been the source of cataclysmic events on cities throughout the world. Unlike many other earth processes, the effects of major earthquakes transcend all political, social, and geomorphic boundaries and can have decided impact on cities tens to hundreds of kilometers from the epicenter. In modern cities, where buildings, transportation corridors, and lifelines are complexly interrelated, the life, economic, and social vulnerabilities in the face of a major earthquake can be particularly acute.

The 1994 Northridge Earthquake was a major test for parts of what many consider the most earthquake-prepared and best-engineered metropolitan region in the United States. While the combined efforts of concerned professionals at all levels of government, academia, and the private sector have produced significant advances in our knowledge of the causes and potential effects of earthquakes, and of ways to reduce their impact, it remains unfortunately true that actual earthquakes provide important opportunities to test those advances in our knowledge.

In the hours and days following the Northridge Earthquake, the four Federal member agencies of the National Earthquake Hazards Reduction Program (NEHRP), the Federal Emergency Management Agency (FEMA), the National Institute for Standards and Technology (NIST), the National Science Foundation (NSF), and the United States Geological Survey (USGS) laid out a detailed plan for collecting, analyzing, archiving, and reporting information that would benefit the Nation in future earthquake hazards reduction efforts. Congress provided a special appropriation to FEMA to carry out this plan and FEMA distributed those funds to the four NEHRP agencies. The USGS was responsible for conducting geophysical and geological investigations in support of the NEHRP Post-earthquake Study.

For the past 2 years, the USGS has rigorously pursued over 40 tasks focused on the USGS Northridge Earthquake Mission. This document is a summary report of the USGS findings; additional technical reports on specific USGS tasks are appearing in various scientific journals and USGS publications.

Contents



Summary

Photo: USGS/D.L. Carver

A Direct Hit on a Modern American City


Photo: USGS/J. Dewey

The Northridge earthquake of January 17, 1994, struck a modern urban environment generally designed for seismic resistance. There were few casualties, but economic cost was high with losses estimated at $20 billion. The earthquake severely tested building codes, earthquake-resistant construction, and emergency preparedness and response procedures. The experience confirmed many of the lessons learned from past earthquakes, exposed weaknesses in the society's generally resilient fabric, and produced many surprises about the levels and consequences of strong ground shaking.

"...well-engineered buildings withstood violent shaking without structural damage."

Near the epicenter in the San Fernando Valley, well-engineered buildings withstood violent shaking without structural damage. However, numerous structural failures throughout the region were evidence of significant deficiencies in design or construction methods. Steel frames of buildings intended for seismic resistance were cracked, and reinforced concrete columns were crushed. Most highway structures performed well, but freeways collapsed at seven sites, and 170 bridges sustained varying degrees of damage.

The Northridge event showed that an earthquake of moderate size can produce intense ground motions in the immediate vicinity of the fault rupture. These findings forced scientists, engineers, and policy makers to rethink the criteria used for designing urban buildings and infrastructure. ◆

USGS Roles and Actions


Photo: USGS/D.L. Carver

The National Earthquake Hazards Reduction Program (NEHRP) agencies reached agreement in March 1994 on task assignments for Northridge earthquake investigations (1994-96) by the U.S. Geological Survey (USGS). Additional tasks were assigned to the USGS under appropriations from the President's Discretionary Fund. This document is a summary of USGS findings on its assigned tasks.

The USGS responded quickly and effectively to the Northridge earthquake, relying on its lengthy national and international experience in disaster response. The USGS office at the California Institute of Technology (USGS/Caltech) quickly became one of the principal organizers of scientific work by other government agencies, universities, and private engineering and geotechnical firms.

"The USGS,...SCEC, and their cooperators engaged in the most successful and well coordinated effort in deploying monitoring instruments ever undertaken following a United States earthquake."

Geographic information systems (GIS) technology and Internet communications were the principal avenues of database and information management for the scientific response. Critical data—including maps and illustrations—were produced by digital means or converted to digital form. This information was then transmitted via the Internet to USGS investigators and to the broader public audience having Internet access.

The USGS, the Southern California Earthquake Center (SCEC), and their cooperators engaged in the most successful and well coordinated effort in deploying monitoring instruments ever undertaken following a United States earthquake. The coordinated effort by the USGS and SCEC assembled sophisticated instrument arrays that were placed and relocated as needed to target specific seismological and engineering issues.

The USGS provided broad communications and liaison response through its offices nationwide. Media relations professionals provided a continuous flow of news to a demanding audience, and liaisons were assigned to governmental decision-making entities on an as-needed basis. ◆

The Earthquake's Setting and Impacts

The Northridge earthquake occurred beneath the San Fernando Valley on a deeply buried blind thrust fault that may be an eastern extension of the Oak Ridge fault system. The fault plane ruptured from a depth of about 17.5 kilometers upward to about 5 kilometers beneath the surface. For 8 seconds following the initial break, the rupture propagated upward and northwestward along the fault plane at a rate of about 3 kilometers per second. Fortuitously, the strongest seismic energy was directed along the fault plane toward sparsely populated areas north of the San Fernando Valley.

"Fortuitously, the strongest seismic energy was directed...toward sparsely populated areas..."

The earthquake deformed the Earth's crust over an area of 4,000 square kilometers, forcing the land surface upward in the shape of an asymmetric dome. The dome manifests features and consequences of blind thrust faulting that might lead scientists to the discovery of similar faults elsewhere. The lack of clear surface rupture in 1994 may be explained by fault movement terminating at depth against another fault that moved in the 1971 San Fernando event.

"... earthquakes should be thought of as regional events that occur over a brief period of time"

The earthquake was felt over more than 200,000 square kilometers of the land area of the United States and Mexico and at distances of 400 kilometers from the epicenter. The shaken area and the patterns of damage were broadly similar to those of the 1971 San Fernando earthquake. Differences in damage patterns in 1971 and 1994 were related to the location of fault planes with respect to the ground surface, and to the propagation of energy toward or away from population centers.

The earthquake illustrates the concept that earthquakes in general should be thought of as regional events that occur over a brief period of time. The fault rupture moved across an underground surface of about 430 square kilometers in about 8 seconds, producing a wide area of effects at the surface. This concept replaces the widely held understanding that earthquakes occur instantaneously at points and are represented by the location of an epicenter.

Geologists continue the search for blind thrust faults throughout southern California by modeling the system of folds and uplifts believed to be produced by slip on these faults. Concurrently, they are mapping the crustal structure of the Earth beneath the region using highly detailed imaging techniques of the Los Angeles Region Seismic Experiment (LARSE). The LARSE is yielding promising results about the tectonic framework that causes earthquakes throughout southern California.

The geological knowledge that bears on understanding and forecasting earthquake hazards is being systematically assembled in a digital database for southern California. The information includes a digital map plus data pertaining to the rates and activity of faults and folds throughout the region. All data are assigned systematic quality ratings to allow database users to make sound judgments when evaluating parameters such as slip rates and other hazards indicators. The digital map and database are intended for widespread access, reviews, and continuous updating using the World Wide Web (WWW). ◆

Evaluating Ground Response


Photo: USGS/M. Rymer

In general, the region closest to the earthquake—the northern San Fernando Valley—sustained the greatest amount of damage. There were also isolated pockets of severe damage in Sherman Oaks, Santa Monica, and other distant locations. This damage was related to a variety of local geological and topographic conditions that bear close scrutiny because such conditions are indicators of potential problems in future earthquakes.

"One of the highest accelerations ever recorded in an earthquake occurred just south of the epicenter in Tarzana."

USGS scientists developed earthquake-shaking indicators (site response factors) for the Los Angeles region that vary depending upon the local geological conditions. Scientists were also able to validate the practice of using data from small aftershocks to predict local site responses to strong ground motions. In addition, scientists developed shear-wave (*s*-wave) velocity relations that further help determine characteristics of site response in the region. This work shows that damage-prone areas can be defined and assessed for damage-mitigation measures prior to the next major earthquake.

One of the highest accelerations ever recorded in an earthquake occurred just south of the epicenter in Tarzana. The 1.78*g* main-shock acceleration occurred atop a small hill, calling attention to the effects of local topography in amplifying seismic energy. Such effects are reminders that broad seismic-design guidelines, based on interpolated contours of peak accelerations, might greatly underestimate local site conditions.

Very deep geological structures affect the amplitude and duration of shaking at the surface of sedimentary basins like the San Fernando Valley. Seismic waves traveling upward from depth are redirected by subtle irregularities in deep geological interfaces, and their energy is focused in certain areas and defocused elsewhere. The waves can be trapped along the edges of the basins, or reflected so that they travel as surface waves across the basins. These effects illustrate some of the reasons for the patterns of damage throughout the San Fernando Valley.

"Soil-amplification factors at several sites were significantly higher than those specified in the NEHRP Recommended Provisions..."

Soil-amplification factors at several sites were significantly higher than those specified in the NEHRP Recommended Provisions for nonlinear soil response. Thus, in order to further mitigate future damages, the amplification factors in the Provisions need to be examined and revised in light of findings from the Northridge earthquake. ◆

Ground Failures and Landslides

The earthquake produced ground failures of many types at distances up to about 90 kilometers from the epicenter. The nature of these failures provided extremely important information for seismic-hazards evaluations that could not be obtained from studying seismogenic faults alone. Widespread ground failures in the San Fernando Valley typically were underlain by both ground water and fine-grained sediments at depths of less than 10 meters. These associations can be used to identify general areas where studies of ground failure potential are advisable.

"...ground failure was the principal cause of damage to single-family homes and buried utilities."

The most extensive belt of ground failures occurred in the Granada Hills-Mission Hills area. There, as at other sites, ground failure was the principal cause of damage to single-family homes and buried utilities. Structures within ground-failure zones suffered nearly three times more damage than nearby structures outside the zones. Foundation damage, which was nearly six times more prevalent in ground-failure zones (and twice as expensive to repair) accounted for most of the additional losses.

"The earthquake caused many thousands of landslides over an area of 10,000 square kilometers..."

The most widely distributed ground failures were associated with filled land where poor performance of loose fills caused significant damage to structures. Fills and dams in the Van Norman Complex, reengineered after failures in the 1971 San Fernando earthquake, showed excellent performance under the stronger shaking of the Northridge earthquake.

The earthquake caused many thousands of landslides over an area of 10,000 square kilometers, mostly concentrated in sparsely populated areas north of the San Fernando Valley. The landslides destroyed homes, roads, and utility lines, and blocked streams. They also generated dense clouds of dust, precipitating an outbreak of valley fever that caused three fatalities. USGS scientists inventoried the landslides and developed a landslide susceptibility map. The map can be used to produce a variety of scenarios of slope failures during postulated future earthquakes of different magnitudes and locations. ◆

Investigating Building and Freeway Damages

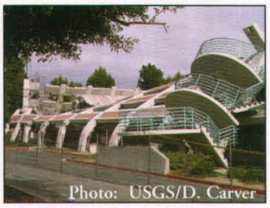


Photo: USGS/D. Carver

Whereas many well-designed buildings and freeway structures performed satisfactorily, there were unexpected failures due to the strong ground motions in the vicinity of the fault rupture. Failures notably included fractured steel frames in more than 100 buildings ostensibly designed for the ground motions produced by the earthquake. Consequently, a program was initiated by a joint venture of structural engineering associations for developing new building codes for steel-frame buildings. Major freeway collapses and damage to more than 170 freeway bridges indicate that, despite a vigorous program of freeway reinforcement since the 1971 San Fernando earthquake, the structures in many places remain vulnerable. Future structural design will need to account for stronger shaking levels than those postulated before the Northridge earthquake.

"...there were unexpected failures (of well-designed buildings and freeway structures) due to strong ground motions in the vicinity of the fault rupture."

The University of Southern California (USC) Hospital building was the first base-isolated structure to provide data on isolator performance during strong shaking. The isolators proved effective in dissipating the vibrational energy of the earthquake. However, the building was located about 35 kilometers from the epicenter, and ground motions at the site were only moderately strong. The displacements measured for sites nearer the fault would have exceeded the designed displacement range of the isolators.

"...peak accelerations during the earthquake generally exceeded those predicted."

The Olive View Hospital building was built for seismic resistance based on the disastrous fate of its predecessor in the 1971 San Fernando earthquake. The redesigned building performed very well during the Northridge earthquake, probably saving many lives in a region of very intense shaking. However, the design placed the fundamental frequency of the building within a frequency range that produced conditions for resonance, causing concern about performance in a larger earthquake. Additionally, nonstructural failures forced evacuation of the building, indicating a need for interior design improvements in anticipation of future earthquakes.

The Holiday Inn in Van Nuys suffered minor damage in the 1971 San Fernando earthquake and major structural damage in the Northridge earthquake. The building vibrations during the Northridge event exceeded the response spectra of both the San Fernando quake and the Uniform Building Code. Engineers also noted a significant amount of torsion in the building response.

The collapsed I-5/SH-14 interchange between San Fernando and Newhall was one of the most spectacular and costliest freeway failures. Scientists determined that peak spectral amplitudes at the bridge during the main shock were three to four times the design spectra for periods less than 1 second. Ground motions at the base of the bridge were effectively transferred to the deck where their amplifications resulted in the collapse.

Studies of more than 250 ground-motion records showed that peak accelerations during the earthquake generally exceeded those predicted. At several locations, horizontal peaks were close to or exceeded 1*g*, and at one station, vertical acceleration exceeded 1*g*. Ground motions both near and far from the fault contained consistent, high-energy pulses of relatively long duration. Midrise to high-rise steel structures designed for lesser motions are particularly vulnerable to these pulses. In general, the ratio of horizontal to vertical shaking was similar to that of past earthquakes, and the motions, although strong, were not unusual. For such shaking, buildings need higher strength and larger ductility to accommodate the motions without damage.

The magnitudes of response spectra for both soil and rock sites exceeded critical parts of the Uniform Building Code spectra. Sites such as those in Newhall and Tarzana that experienced unusually high accelerations bear further consideration for special designs to withstand such accelerations.

The USGS developed a new shaking-intensity estimator (called the tagging intensity) that allowed analysis of the relative vulnerability of several categories of residential structures. Post-1940 single-family dwellings constituted both the largest building category and the strongest in terms of resistance to damage. Post-1940 multi-family dwellings proved to be more susceptible to shaking damages than masonry buildings or pre-1940 single-family and 2-to-4-family wood-frame dwellings. The data for Los Angeles County yielded the most detailed estimates of damage and shaking intensity ever obtained for an earthquake in the United States.

"The Los Angeles City program to retrofit unreinforced masonry (URM) buildings was one of the real successes of earthquake preparedness."

The Los Angeles City program to retrofit unreinforced masonry (URM) buildings was one of the real successes of earthquake preparedness. Many of the several thousand buildings retrofitted since 1982 were strongly shaken by the Northridge earthquake, and most survived without the total collapse previously expected for such structures. The URM and other pre-event mitigation programs demonstrate the success of hazards-mitigation measures and validate market incentives for employing the measures. ◆

Photo: USGS/J. Dewey

Updating Seismic Hazards Assessments

The USGS constructed new seismic-hazards maps for the southern California region using information from the Northridge earthquake and accounting for the presence of blind thrust faults. For the region, the San Bernardino area continues to be the highest hazard zone based on its proximity to both the San Andreas and San Jacinto faults. Including blind thrust faults tends to raise the seismic hazard by about 15% for areas near the faults. Differences between maps produced before and after the Northridge earthquake are notable in the area of central Los Angeles where probabilistic accelerations increase from 38%*g* to 45%*g* with the inclusion of blind thrust faults.

Geologic studies at Potrero Canyon exposed evidence of two other earthquakes that likely occurred on buried thrust faults within the past 1,300 years. Part of the Sierra Madre fault—the source of the 1971 San Fernando earthquake—was investigated independently, and geologists determined that only two earthquakes (including the 1971 event) occurred on this segment in the past 3,500-4,000 years. Neither of these, nor earthquakes farther north on the San Andreas fault, produced evidence of their shaking at the Potrero Canyon site. Thus, the geological conditions at Potrero Canyon and similar sites offer promise for determining the frequency of earthquakes from blind thrust faults in the region. Additional evidence from the geological investigations suggests that M = 6.5-

7.0 events are perhaps characteristic of thrust-fault structures.

USGS scientists developed a method for estimating the levels of shaking that future earthquakes will produce. The method provides realistic, broadband ground motions that represent the range and variability of ground motions from the Northridge earthquake as well as earthquakes postulated for other faults in the region. The method allows real or synthesized strong-motion data to be extrapolated over an area of about 3,600 square kilometers of southern California. An investigator using the method can interpolate within this area to estimate, for example, alternative engineering-design characteristics for a given site.

"USGS scientists developed a method for estimating the levels of shaking that future earthquakes will produce."

In the aftermath of the 1971 San Fernando earthquake, the new Los Angeles Dam was designed to withstand shaking about three times stronger than that previously assumed. When the dam was tested by the Northridge earthquake, it showed only minor deformation and superficial cracking compared to its predecessor that nearly failed catastrophically in 1971. This success story helps validate the need to build critical structures more resistant to the violent shaking now recognized to accompany large earthquakes. ◆

Facilitating Communications

This report is part of a new multimedia approach for reporting USGS findings. The approach takes advantage of World Wide Web (WWW) technology to allow for a variety of views and levels of detail to be expressed to a broad spectrum of information users. A WWW tour of the Northridge earthquake investigations and findings is based on this report, and designed as a "living" entity that is updated as new information becomes available.

The USGS and Caltech have substantially improved seismic recording and reporting in southern California, and are now using the system for many applications beyond research. Notably, the system can now be used for estimating the extent of damage from an earthquake within a few minutes of detection of shaking, and reporting this information to all public and private organizations that engage in rapid response. The shaking-intensity map produced shortly after the earthquake was the first use of such a map to help focus relief efforts during a disaster. The seismic recording system also has promise for use in early warning of strong shaking, perhaps providing precious seconds of response time prior to the arrival of the strongest seismic waves.

"The shaking-intensity map produced shortly after the earthquake was the first use of such a map to help focus relief efforts during a disaster."

"The seismic recording system also has promise for use in early warning of strong shaking..."

The USGS and several collaborators are rapidly upgrading a prototype Global Positioning System (GPS) array throughout southern California. This system provides a new baseline for studying compression of the Earth's crust by continuously measuring small displacements that may be indicators of stress accumulation on blind-thrust faults.

"The USGS and its cooperators produced (and distributed throughout southern California)...several thousands of the magazines and fact sheets (and) two million copies of the handbook."

In addition to its scientific documents, the USGS and its cooperators produced many specialty products to communicate findings about the Northridge earthquake. These included magazines, fact sheets, and a personal handbook for earthquake safety for southern Californians. These products were intended for wide distribution, and printed in quantities ranging from several thousands of the magazines and fact sheets to two million copies of the handbook. Many of these products were also adapted to the World Wide Web where they are accessed regularly by Internet users. ◆

Creating Policies and Plans for Seismic Safety

The USGS participated on the interagency team that developed 1994 post-earthquake updates and new provisions for the California Earthquake Hazards Reduction Program. The update, published separately in 1994, will be fully integrated into the State planning document, *California at Risk*, in late 1996. *California at Risk* is a prime example of the link between scientific findings and applying those findings to earthquake hazards reduction throughout California.

"Throughout the Nation, ongoing research by the USGS and other NEHRP agencies continues to improve the understanding and awareness of earthquakes."

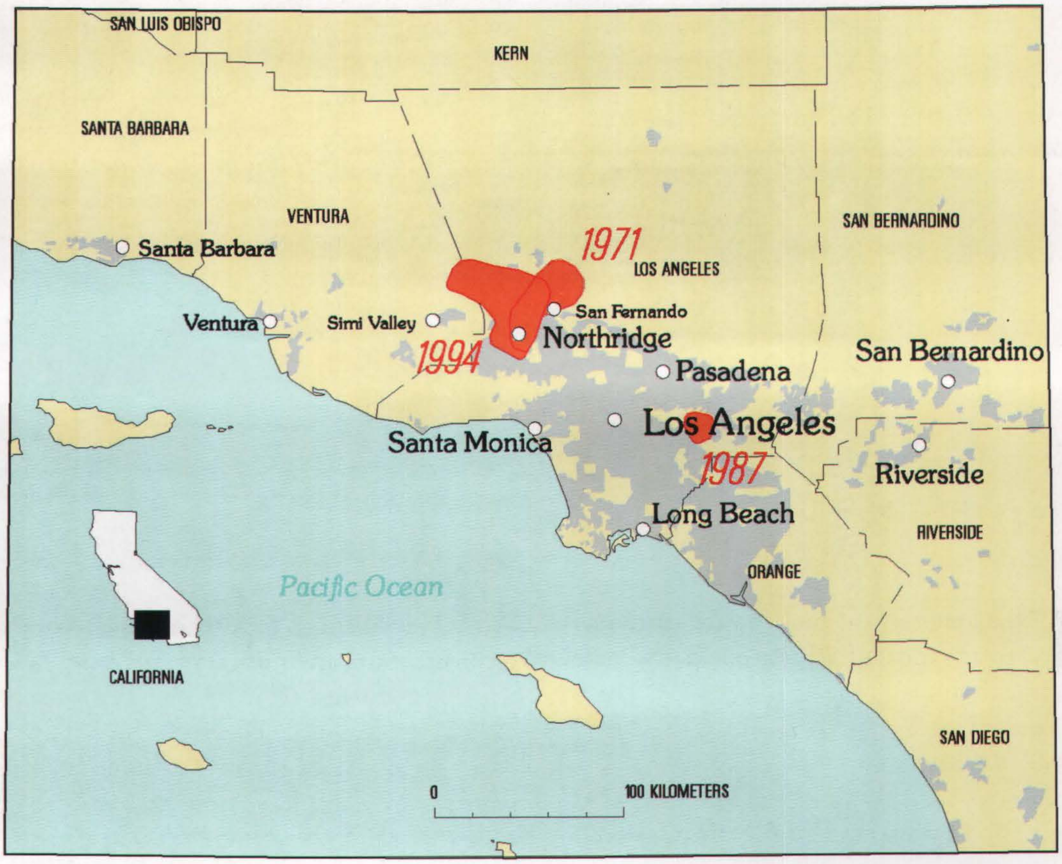
Throughout the Nation, ongoing research by the USGS and other NEHRP agencies continues to improve the understanding and awareness of earthquakes. The advances translate into model policies and other lessons that need to be applied nationwide as other regions at risk develop stronger seismic safety programs. The USGS response to the Northridge earthquake, taken in its entirety from scientific research to policy-making, demonstrates multi-agency cooperation, communication, response, coordination, and relevance. ◆

Introduction

Photo: Associated Press / Douglas C. Pizac

The Earthquake and Its Impacts

At 4:30 on the morning of January 17, 1994, some 10 million people in the Los Angeles region of southern California were awakened by the shaking of an earthquake. The earthquake, named for its epicenter in the town of Northridge, was a magnitude 6.7 (M = 6.7) shock that proved to be the most costly earthquake in United States history. The shaking heavily damaged communities throughout the San Fernando Valley and Simi Valley, and their surrounding mountains north and west of Los Angeles, causing estimated losses of 20 billion dollars. Fifty-seven people died, more than 9,000 were injured, and more than 20,000 were displaced from their homes by the effects of the quake. Although moderate in size, the earthquake had immense impact on people and structures because it was centered directly beneath a heavily populated and built-up urban region. Thousands of buildings were significantly damaged, and more than 1,600 were later "red-tagged" as unsafe to enter. Another 7,300 buildings were restricted to limited entry ("yellow-tagged"), and many thousands of other structures incurred at least minor damage. The 10-20 seconds of strong shaking collapsed buildings, brought down freeway interchanges, and ruptured gas lines that exploded into fires. Fortuitously, the early morning timing of the earthquake spared many lives that otherwise might have been lost in collapsed parking buildings and on failed freeway structures. ◆



The 1994 Northridge earthquake (M = 6.7) occurred in a heavily populated urban area northwest of Los Angeles and had many similarities to the 1971 San Fernando earthquake (M = 6.7) and the 1987 Whittier Narrows (M = 5.9) earthquake. The three shocks, their aftershock zones (shown with red shading), and their effects on the surrounding cities and towns are compared throughout this report.

The Early Response—Collecting Information and Organizing Communications

Scientists of the U.S. Geological Survey (USGS) responded quickly to the Northridge earthquake, many arriving on the day of the quake to investigate and report on its geological and engineering effects. Early on January 17, the USGS office at the California Institute of Technology (Caltech) in Pasadena became the center for information processing. The network of seismic instruments for monitoring earthquakes in southern California is operated jointly with the USGS at Caltech and, within minutes of the main shock, scientists were analyzing data and broadcasting information about the quake to the public. Scientists maintained a steady flow of public information over the next few days as details about the earthquake and its effects were gleaned from seismic data and observed by field crews. The USGS maintained communications with emergency-response agencies using a liaison stationed at the nearby Federal Emergency Management Agency (FEMA) Disaster Field Office, while hosting at Caltech a liaison from the California Governor's Office of Emergency Services (OES). The USGS continued data processing, communications, and liaison efforts throughout the following months while disaster cleanup continued and the Los Angeles area was rocked by hundreds of aftershocks. ◆

A USGS office is located at Caltech in Pasadena. The USGS and the Caltech Seismological Laboratory cooperate to maintain the Southern California Seismic Network (SCSN), process and archive earthquake information, conduct scientific research, and make earthquake data accessible to scientists and the public.

The Long-Term Response—New Experience with an Urban Earthquake

The long-term response to the earthquake by the four NEHRP agencies (National Science Foundation, National Institute of Standards and Technology, FEMA and the USGS) was based upon four objectives. First, the agencies needed to apply their capabilities immediately by assisting local, State, and Federal jurisdictions to carry out the recovery, reconstruction, and mitigation processes in the aftermath of the quake. Secondly, the agencies needed to commence investigating a sequence of events associated with the earthquake. This sequence of events leads from the earthquake source, through the earth into the built environment, to the resultant economic and social impacts, and finally the response. Studying this continuum helps reveal the lessons the earthquake has to teach. As those lessons were revealed, the third objective was to collaborate in communicating the lessons throughout society. Finally, the lessons needed to be applied both in southern California and, as appropriate, throughout the rest of the United States. ◆

The Tasks of the NEHRP Agencies

By March 14, 1994, the four NEHRP agencies had reached consensus on the highest priority post-earthquake investigations and activities to be funded by emergency disaster appropriations by Congress. In all, 84 specific tasks were assigned to the NEHRP agencies under the March 14 agreement, and an additional 22 tasks were assigned later under appropriations from the President's Discretionary Fund. In general, the tasks were to be completed within a period of about 2 years. The tasks were specifically oriented toward a timely, effective response to the Northridge earthquake, with longer term goals of readying the region and the nation for inevitable, future earthquakes. This document reports on the tasks assigned specifically to the USGS and summarizes the accomplishments of scientific investigations since the earthquake. ◆

Comparing Urban Earthquakes—Northridge, California, and Kobe, Japan

Exactly 1 year after the Northridge earthquake, on January 17, 1995, a devastating earthquake struck the city of Kobe, Japan. This $M = 6.9$ event produced a massive disaster that overshadowed the impacts of the Northridge quake. In Kobe, 5,100 people died, 27,000 were injured, and 100,000 buildings were destroyed. The vast destruction, heavy casualties, and economic losses in both earthquakes underscore the importance of bettering our understanding and forecasting seismic hazards in urban areas. Earthquakes larger than those in Northridge and Kobe are certain to strike our cities and towns sometime in the future. The USGS approach to earthquake response and the studies that follow are the basis for the understanding needed to reduce life and property losses when the inevitable earthquakes occur.

Frequency of M = 6.0-6.9 Earthquakes Worldwide

Thousands of earthquakes occur around the world every day, although most are so small they can only be detected by sensitive seismographs. As more and more seismographs are installed, more earthquakes can be located. The number of large earthquakes ($M = 6.0$ and greater) has stayed relatively constant, based on observations since 1900. For example, an average of 120 earthquakes per year worldwide in the magnitude range of 6.0 - 6.9 (like the Northridge and Kobe events) have occurred since 1900. For the past decade, the annual number of $M = 6.0$ - 6.9 shocks worldwide has ranged from 79 in 1989 to 141 in 1993. These numbers tell us that events like those affecting Northridge and Kobe are not unusual, and that we should be prepared for such shocks wherever our cities and towns are located in seismically active areas.

Assisting Recovery, Reconstruction, and Mitigation

Photo: Los Angeles Times / David Bohrer

The Immediate Response—Working with Others During the Aftermath of the Earthquake

Rapid Deployment of Seismic Instruments

The USGS and its cooperators have become highly skilled and efficient in rapidly deploying a widespread array of seismic instruments following earthquakes. Instrument deployment following the Northridge event proved to be one of the most successful and well coordinated efforts ever produced following a United States earthquake. Led by the USGS and SCEC, the effort included seven universities, four USGS teams, and contributions from several private companies. More than 80 instruments were placed in dense arrays, then relocated as needed in various configurations to address specific seismological and engineering issues.

All modern disasters in the United States are met by immediate and long-term demands from Federal, State, and local government agencies for practical information during response and recovery efforts. Some of this information is needed to meet requirements for receipt of Federal disaster funds; some of it is needed for the standards, guidelines, and practices to be used during repairs, rebuilding, and land-use planning. All NEHRP agencies, while engaging in rapid emergency response, are tasked with meeting the demands for information and assisting the many entities in interpreting what the information means.

The USGS brings lengthy experience to disaster response that arises from decades of response to and research on a variety of natural disasters, both national and international. Thus, the nature of its response is reflected in a continuously improving, multifaceted program, planned and operated by people with significant training and practice. The scientific response is a major element. In general, responding scientists have considerable foreknowledge of possible earthquake effects and the areas where these effects are likely to be encountered. In southern California, the rapid outputs from vast arrays of scientific instruments also help guide investigators in making efficient logistical decisions. Responders in the field work individually or in small teams, typically in topical areas such as building-damage assessments, liquefaction, ground rupture, or instrument placements. Others, even at sites elsewhere in the country, begin the process of data analysis, coordinating their activities through a central processing facility. Scientists are in constant communication, posting current information on the Internet, and distributing it widely using large E-mail dissemination programs. Moreover, the USGS typically becomes the official entity for organizing scientific work by other government agencies, universities, and private engineering and geotechnical firms following earthquakes. Notably, the USGS works in concert with university scientists of the Southern California Earthquake Center (SCEC) in this coordinating role.

In the case of the Northridge earthquake, the central processing facility was at the USGS office at Caltech. In addition to the scientific response, the USGS provided communications and liaison responses. Communications following the Northridge quake were handled primarily through USGS/Caltech, the National Earthquake Information Center (NEIC) in Golden, Colorado, and USGS offices in Menlo Park, California, and Reston, Virginia. USGS scientists also shared information and coordinated activities with other agencies and institutions as key participants in the California Division of Mines and Geology/Office of Emergency Services (CDMG/OES) technical clearinghouse in Pasadena. At each site, professionals trained and experienced in media relations, and in interpreting scientific information from the quake, provided a continuous flow of news to a demanding audience. The media relations functions of the USGS were critical to the smoothness of the government's overall response in the post-earthquake atmosphere of fear and uncertainty. The USGS also provided liaisons to FEMA's Federal Interagency Disaster Response Team, and to decision-making entities at all levels of government on an as-needed basis. The USGS also hosted liaisons from other government agencies to help meet their response, recovery, and long-term planning needs. ◆

The Southern California Earthquake Center (SCEC)

SCEC actively coordinates research on southern California earthquakes and focuses on applying earth sciences to earthquake-hazards reduction. Founded in 1991, SCEC is a NSF Science and Technology Center with administrative and program offices located at the University of Southern California. It is cofunded by the USGS and FEMA. The core institutions of SCEC are: University of California, Los Angeles; University of California, Santa Barbara; California Institute of Technology; Scripps Institution of Oceanography; University of California, San Diego; University of Southern California; Columbia University; and the USGS.

Database Management—The Basis for Effective Response, Recovery, and Mitigation

Rehabilitation, reconstruction, and land-use planning following an earthquake are most effective when data for decision making are easily accessible and internally consistent. The important databases—cultural, geological, geophysical, infrastructure, and political, for example—serve decision making best if they have both geographic uniformity and accessibility at a variety of scales. Recognizing these requirements, the USGS adopted two principal avenues of database and information management: (1) collate, analyze, and synthesize data using geographic information systems (GIS) technology; and (2) publish and distribute data, research results, and other information using the Internet, particularly the World Wide Web (WWW). Both avenues were ideally suited to the role of the USGS as one of the Federal agencies using geographic information systems and WWW technologies.

The Computer Graphics Laboratory (CGL) in Golden, Colorado, provided most of the USGS database support for the Northridge earthquake. The CGL provided (1) advanced computer hardware and GIS software; (2) assistance and training for scientific investigators in using GIS; (3) scientific visualization technology; (4) development of a file-transfer protocol (FTP) data server for distributing digital spatial data among USGS scientists; and (5) development of a WWW site for distributing databases, maps, and reports. Most of these provisions were extended to USGS offices in Menlo Park and Pasadena, California, to enhance capabilities there.

With very few exceptions, maps and illustrations critical to and developed from the earthquake response were produced by digital means, and all data sets were obtained in or converted to digital form. Such digital information could then be readily transmitted via the Internet to USGS investigators and, when reviewed and released, to the broader public audience having Internet access. In this manner, new data and interpretations on the Northridge earthquake response were rapidly and frequently made available to a wide audience in the months following the main shock. All digital maps and illustrations could then be accessed and duplicated at a variety of scales for different scientific applications.

The USGS rapidly produced GIS-based maps incorporating general levels of ground shaking, local site-amplification values, and areas of potential ground failures. These maps were

Whether as scientists, data analysts, media relations professionals, or agency liaisons, USGS personnel respond immediately to indications of an earthquake disaster. Typically, magnitude and location information on earthquakes worldwide are interpreted by the USGS within minutes of a major quake, thereby setting in motion the response for that event. The USGS routinely practices and updates its earthquake response plans, both internally and in cooperation with other government agencies and private entities.

intended for broad uses, and they were targeted for the lengthy reconstruction period when decisions needed to be made regarding standards for rebuilding and repairs. Other maps were created to display data sets, such as the data set on damaged structures provided by the California OES/FEMA Disaster Field Office. This map showed the geographic distribution of inspected buildings that were "red-tagged" (no occupancy), "yellow-tagged" (limited entry), and "green-tagged" (no restrictions on entry). Such maps and their applications are discussed throughout this report (see p. 55). One of the products of the USGS efforts is a large GIS database of maps, data sets, and thematic data layers. These products, many of which are described in this document, will be publicly available at a WWW site. ◆

Communicating via the Internet

As part of its modern communications systems, the USGS customarily provides digital information for (and accesses data from) others on the Internet using an "anonymous" FTP site on one of its host computers. Following the Northridge earthquake, the USGS acquired and distributed data sets many times by the anonymous FTP method, and assisted in preparations of digital publications. One example is the report, *Inventory of Landslides Triggered by the 1994 Northridge, California, Earthquake*, available with the data sets used to produce it via "anonymous" FTP at:

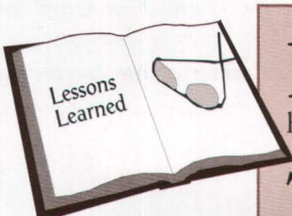
ftp://greenwood.cr.usgs.gov

A hypertext version of the same report, including graphics and photographs, is available on the WWW at:

http://gldage.cr.usgs.gov/html_files/ofr95-213/TABLE.HTML

A principal goal was to establish a WWW site for consolidating all relevant linkages to USGS and other research on the Northridge earthquake. Although many individuals and groups established WWW "home pages" to display data, images, and reports, the USGS has unified these with a single "home page" dedicated to the Northridge earthquake. Access this site on the WWW at:

http://gldage.cr.usgs.gov/northridge/



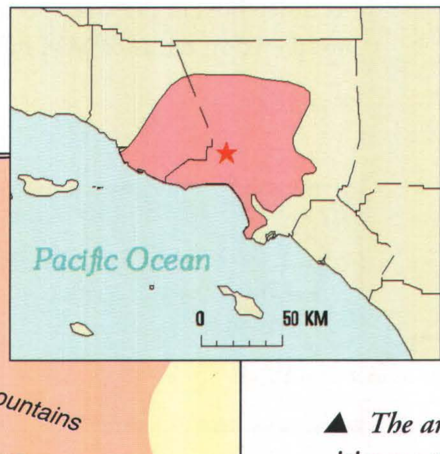
Because all relevant spatial data (commonly produced at great cost) ultimately become digital through GIS and other visualization technologies, these data and their interpretations have an added value through being accurate, easily updated, and transportable.

The USGS decided to include applied technology (Internet; GIS) as an integral part of the post-earthquake research program. This action transformed typical map production into integrated scientific collaboration among scientists and the Computer Graphics Laboratory. The new procedures arising from this collaboration achieved superior results in increasing the efficiency of scientific investigations and communicating their findings.

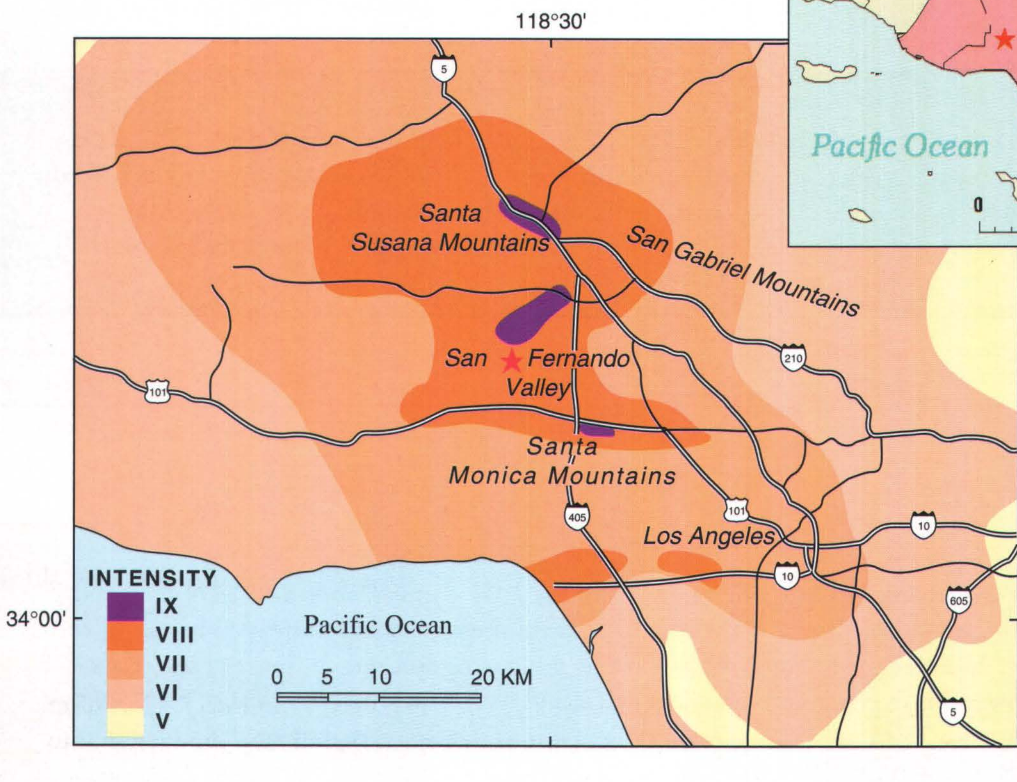
Damage and Intensity Inventories

To determine the intensity and areal extent of earthquake damage, USGS scientists conducted reconnaissance field trips and queried thousands of individuals by telephone during the first week after the main shock. Additionally, they collected information from press reports, mailed questionnaires, E-mail responses to requests for information broadcast over the Internet, reconnaissance reports from other entities such as engineering firms, and from data on the distribution of "red-tagged" buildings and "yellow-tagged" buildings.

The data showed that the earthquake was felt over approximately 214,000 square kilometers of the land area of the United States. The earthquake was also felt in Ensenada, Mexicali, and Tijuana, Mexico. The earthquake was felt 400 kilometers to the northwest in Turlock in California's Central Valley and 375 kilometers to the northeast in Las Vegas, Nevada. Damage throughout this region was described, tabulated, and entered into a geographic database that was later accessed for a variety of decision-making purposes.



▲ *The area including intensities greater than or equal to Modified Mercalli intensity VI extends from the mouth of the Santa Clara river in Ventura County eastward throughout most of the Los Angeles area. Star indicates epicenter of the Northridge earthquake in both figures.*

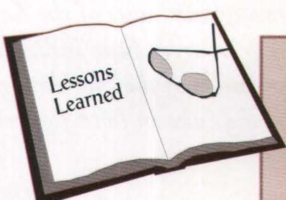


The distribution of Modified Mercalli intensities (MMI) in the epicentral region shows a maximum intensity of IX for three locations in the San Fernando Valley. Intensity IX means "Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground Pipes Broken."

The intensity pattern of the Northridge earthquake is broadly similar to that of the 1971 San Fernando earthquake. In detail, the intensity VII and VIII isoseismals of the Northridge earthquake enclose larger areas than the corresponding isoseismals of the San Fernando earthquake. The intensity V and VI isoseismals of the Northridge earthquake enclose smaller areas than those of the San Fernando earthquake. The maximum intensity assigned to the Northridge earthquake was IX, and the maximum intensity assigned to the San Fernando earthquake was XI. These differences perhaps reflect (1) real differences in the level of ground shaking, (2) systematic changes over time in the damage susceptibility of structures, (3) differences in the distribution of observations, and (4) differences in the way specific effects are interpreted in terms of MM intensities.

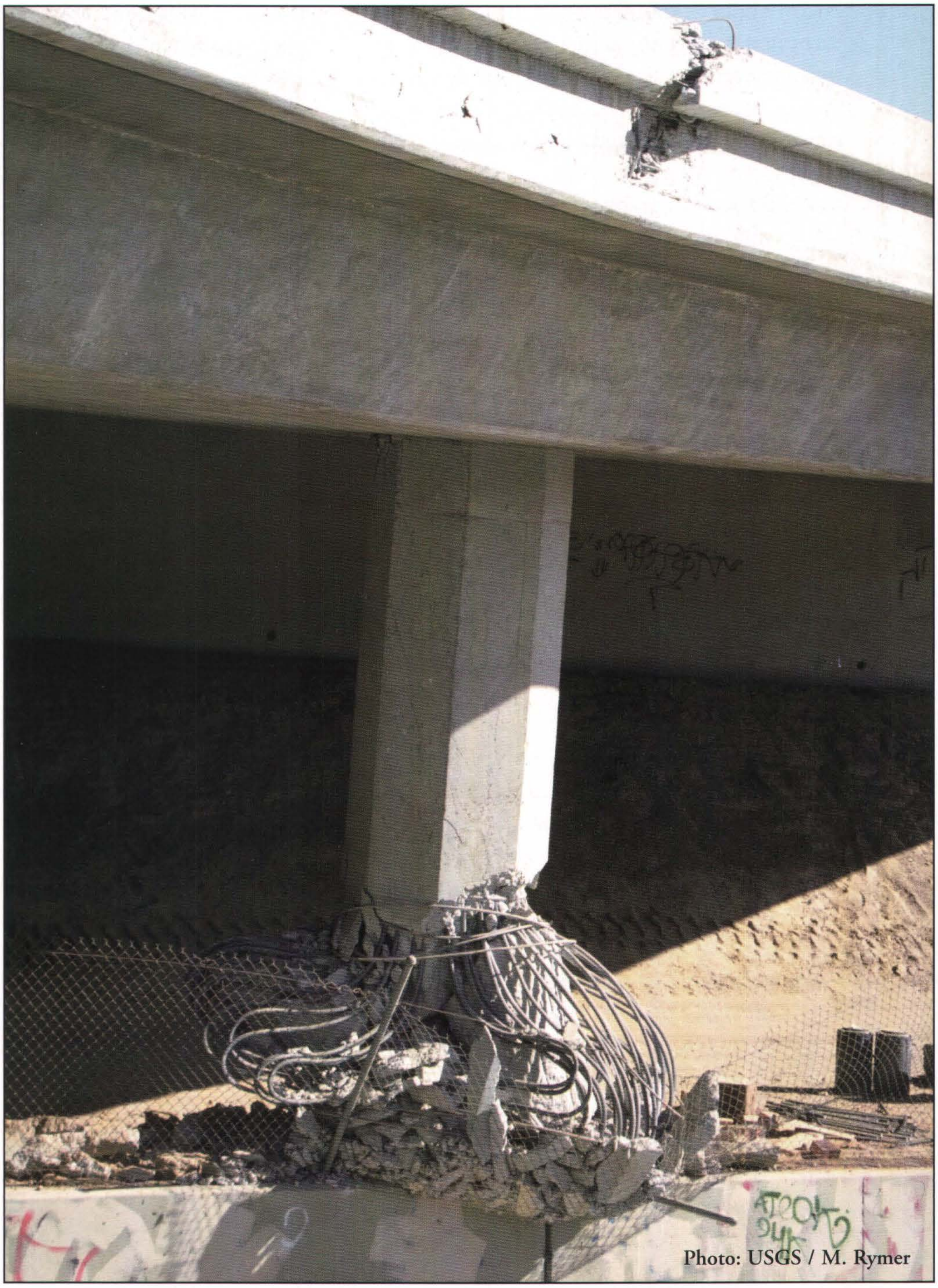
Real differences in the distributions of ground shaking in the two events result from differences in the sources of the two earthquakes. First, the locations of the energy release in the two shocks were separated by about 20 kilometers. Second, the 1971 fault rupture nucleated at depth beneath a lightly populated mountain range and propagated southward toward a heavily populated valley. The 1994 rupture nucleated at depth beneath a heavily populated valley and propagated northward toward a region of lightly populated mountains and valleys. Third, the primary 1971 fault rupture broke through to the ground surface, whereas the primary 1994 fault rupture terminated several kilometers below the surface (see p.16). ◆

Unlike the Richter magnitude scale, which is a measure of the energy release at the earthquake source, Modified Mercalli Intensity refers to the observed effects of ground shaking at individual localities. Seismologists assign intensity to specific sites on the basis of the observed severity of shaking, damage to buildings, and changes in the landscape.



Comparing Modified Mercalli intensities of the 1971 San Fernando and 1994 Northridge earthquakes shows broad similarities because of the similar magnitudes and types of faulting of the two events. However, the two events differed significantly in the location of their fault planes with respect to the ground surface, and with respect to the propagation of energy toward or away from major population centers. Thus, the San Fernando quake probably produced higher intensities in some locations because of the orientation of its fault plane, and because rupture on that plane reached the land surface.

Studying the Setting and Consequences of the Earthquake



The Main Shock

The Northridge earthquake began as a rupture on a hidden fault at a depth of about 17.5 kilometers beneath the San Fernando Valley. For 8 seconds following the initial break, the rupture propagated upward and northwestward along the fault plane at a rate of about 3 kilometers per second. The rupture front spread out across the fault plane, so that the eventual size of the rupture covered an area of approximately 15 by 20 kilometers. The rupture then terminated at a depth of about 5-6 kilometers. Using data from 38 of the more than 200 accelerographs throughout southern California, and data from other instruments and land surveys, scientists were able to make an accurate portrayal of the dynamic properties of the movement along the fault.

Earthquakes are broad, areal events that move through time and space. The main shock and aftershock areas of three recent earthquakes in the Los Angeles region show the approximate dimensions of fault slip beneath the land. Note the overlap of the 1994 Northridge event (M = 6.7) and the 1971 San Fernando event (M = 6.7). Like the Northridge earthquake, the smaller Whittier Narrows event of 1987 (M = 5.9) occurred on a blind thrust fault. Principal faults exposed at the surface (purple lines) and urbanized areas of southern California (gray shaded area) are shown for comparison.

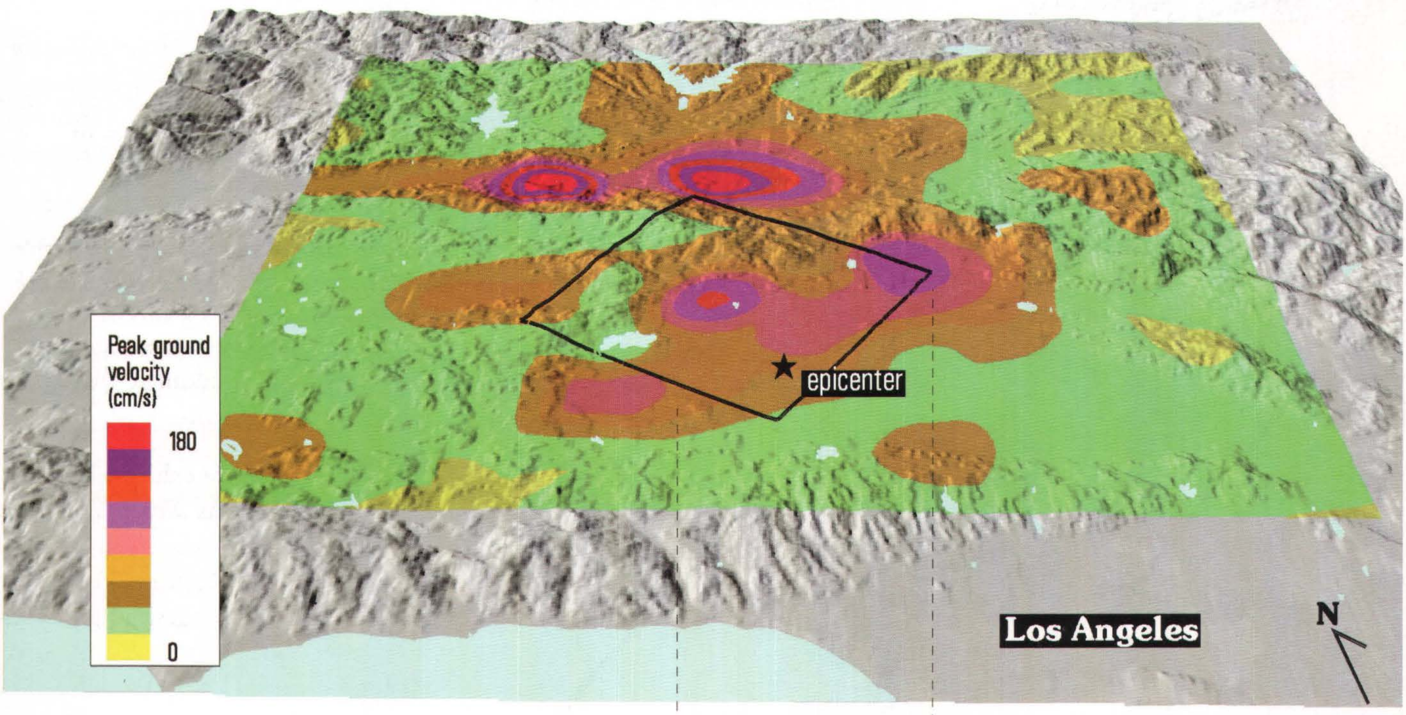
The fault movements were characterized by at least three distinct subevents, or pulses of motion, a few seconds apart. The initial subevent came from an ***asperity*** (p. 14) that began at the hypocenter and extended upward (updip). Another large subevent was centered about 12 kilometers updip to the north from the hypocenter. A third subevent radiated from a high-slip region about 19 kilometers deep, 8 kilometers west-northwest of the hypocenter.

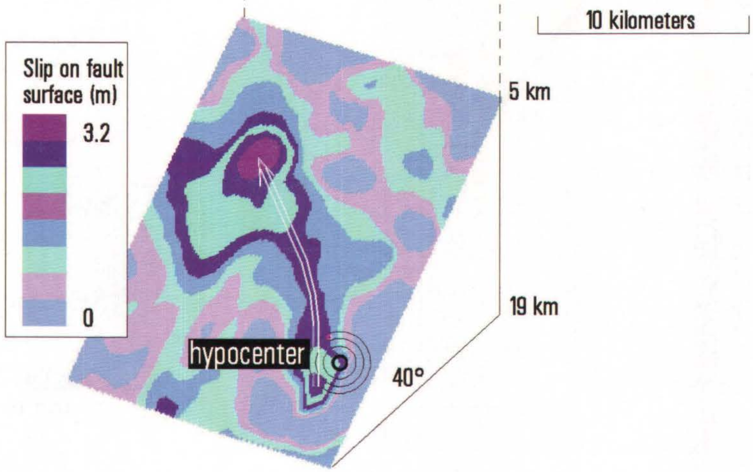
The Northridge earthquake exhibited an amplification effect, known as ***directivity***, where the amplitude of the seismic waves was larger in the forward direction of the rupture. Fortuitously, this resulted in the strongest long-period (1-3 second) ground motions accruing in areas north of the San Fernando Valley that were sparsely populated. Also, this region had few larger steel- or concrete-frame structures which are especially vulnerable to energy of periods in the range of 1-3 seconds. Consequently, ground motions in the most populated and built-up areas of the valley to the south were modest relative to those in the Santa Susana Mountains and the Santa Clara River valley.

For engineering design and hazards assessment during the recovery process, scientists estimated ground motions throughout the region to fill in broad areas where no direct instrumental measurements were made (see p. 65). Estimates were based on a model developed for the fault-plane rupture, and allowed for analysis of damage potential over the entire near-source region. The estimates took into account, for example, the longer period directivity pulses, while realistically representing higher frequency accelerations needed for engineering design. ◆

Accelerograms, the recordings from strong-motion accelerographs, contain information about the large-amplitude seismic waves in the region close to large earthquakes. This information is used primarily by engineers to help establish seismic safety codes for future earthquakes. It is also used by seismologists to understand the details of the fault-rupture process and the complicated wave propagation effects that control the intensity of earthquake shaking.

This perspective aerial view of the Los Angeles region from the south illustrates how the Earth ruptured beneath the San Fernando Valley and shows some of the effects the resulting earthquake had on the land above.





Effects at the Land Surface ▲

Color tints on the surface show the distribution of peak ground velocities inferred from strong-motion accelerograms. The rectangle is the projected outline of the subsurface fault plane, and the star is the epicenter, the point on the land surface directly above the hypocenter. The highest values of peak ground velocities occurred about 15 kilometers north and west of the epicenter. These high values are thought to be the result of the movement of a block of earth upward and to the northwest, and to the shock being amplified in sedimentary basins.

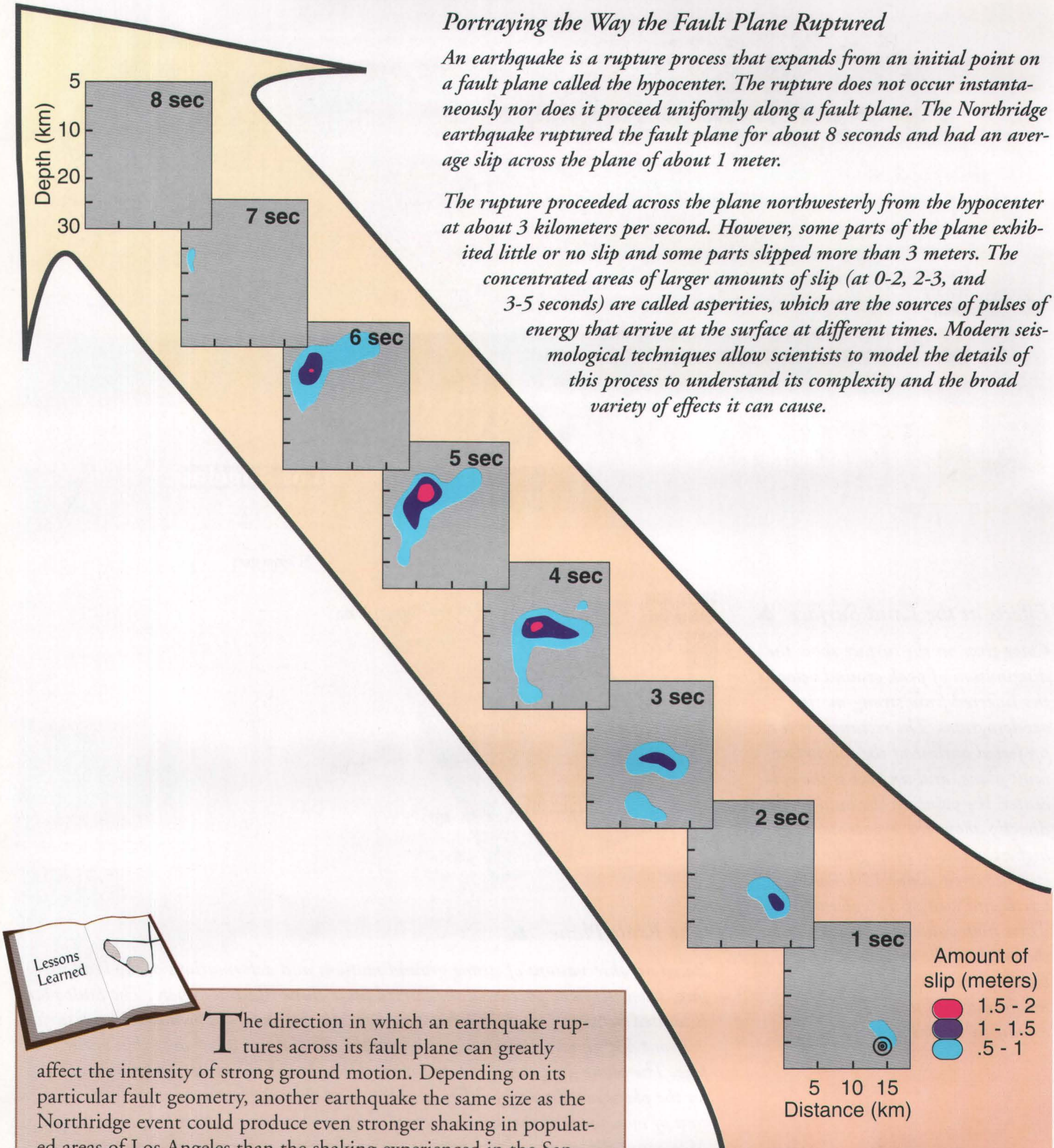
The Fault Plane ▲

Based on observations of strong ground motions and deformations of the land surface, scientists have portrayed the buried fault plane illustrated here. The fault plane is located between 5 and 19 kilometers beneath the surface. The modeled slip surface is about 430 square kilometers, although the slip did not occur over that entire surface. The plane dips about 40° to the south-southwest. The inferred amounts of slip on the plane are shown by different colors, and the color patterns suggest the progression of movement of the upper block of earth with respect to that below the plane. Maximum slip on the plane, seen in the northwest quadrant, was about 3 meters. Apparently, movement that began at the hypocenter in the southeast quadrant generally proceeded upward and to the northwest (arrow). (Note that the plane is shown displaced well below the surface.)

Portraying the Way the Fault Plane Ruptured

An earthquake is a rupture process that expands from an initial point on a fault plane called the hypocenter. The rupture does not occur instantaneously nor does it proceed uniformly along a fault plane. The Northridge earthquake ruptured the fault plane for about 8 seconds and had an average slip across the plane of about 1 meter.

The rupture proceeded across the plane northwesterly from the hypocenter at about 3 kilometers per second. However, some parts of the plane exhibited little or no slip and some parts slipped more than 3 meters. The concentrated areas of larger amounts of slip (at 0-2, 2-3, and 3-5 seconds) are called asperities, which are the sources of pulses of energy that arrive at the surface at different times. Modern seismological techniques allow scientists to model the details of this process to understand its complexity and the broad variety of effects it can cause.



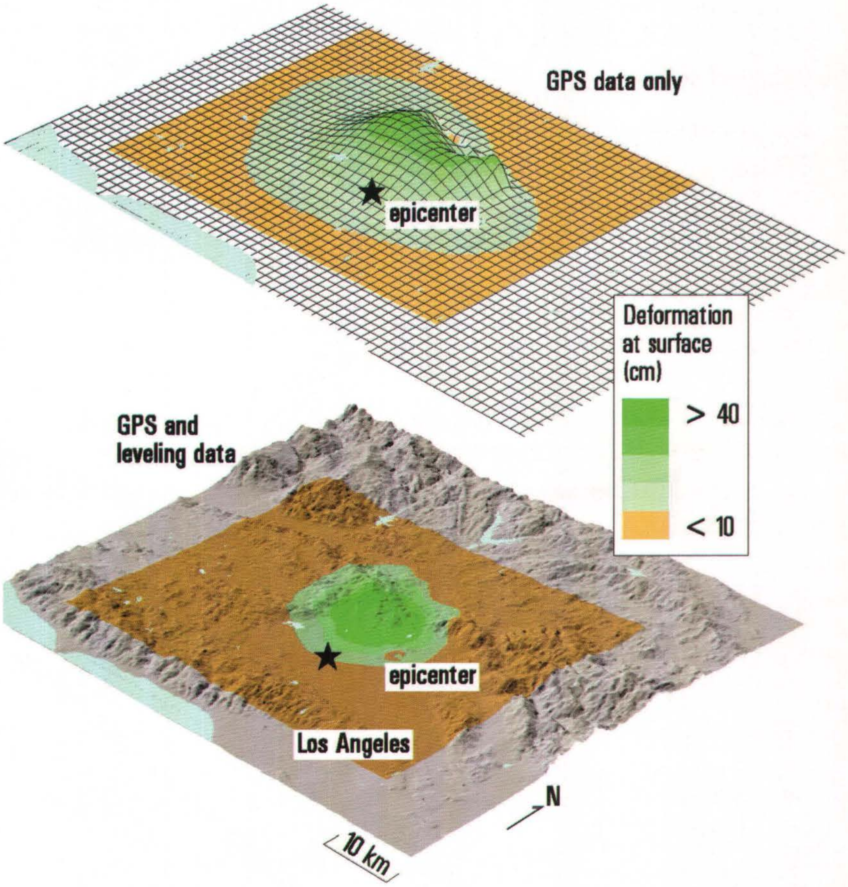
The direction in which an earthquake ruptures across its fault plane can greatly affect the intensity of strong ground motion. Depending on its particular fault geometry, another earthquake the same size as the Northridge event could produce even stronger shaking in populated areas of Los Angeles than the shaking experienced in the San Fernando Valley during 1994.

How the Earthquake Changed the Dimensions of the Land

The Northridge earthquake significantly deformed the Earth's crust over an area of about 4,000 square kilometers. In general, the earthquake caused uplift throughout the San Fernando Valley and adjacent mountain areas. The Santa Susana Mountains were pushed up by at least 40 centimeters, based on direct measurements at Oat Mountain, and possibly by as much as 52 centimeters, based on modeling slip on the fault plane. The northern edge of the San Fernando Valley was pushed up less than the mountains, but uplift of more than 20 centimeters was measured in Northridge, and as much as 20-40 centimeters of uplift occurred throughout the northern part of the valley.

Over the region of largest slip on the fault plane (see p. 13), the land surface was pressed into an asymmetric dome-shaped uplift. Here, the largest horizontal movements (up to 22 centimeters) also occurred, with displacements outward from the apex of the dome. Significant shortening at the north-northeast and south-southwest margins of the domed area indicates the net compression between the upper and lower blocks of crust that moved during the earthquake.

USGS scientists measured vertical and horizontal displacements using a total of 534 occupations of 66 survey stations during 92 field sessions. These data were combined with continuously recorded Global Positioning System (GPS) data covering 24 hours on the days of each field session. The data were compared with pre-earthquake data collected within 15 months before the earthquake. The resulting data set is of high quality and potentially high utility in understanding the earthquake. The data quality promises to lead to modeling efforts more advanced than the preliminary modeling used to describe the earthquake source for this report. ◆

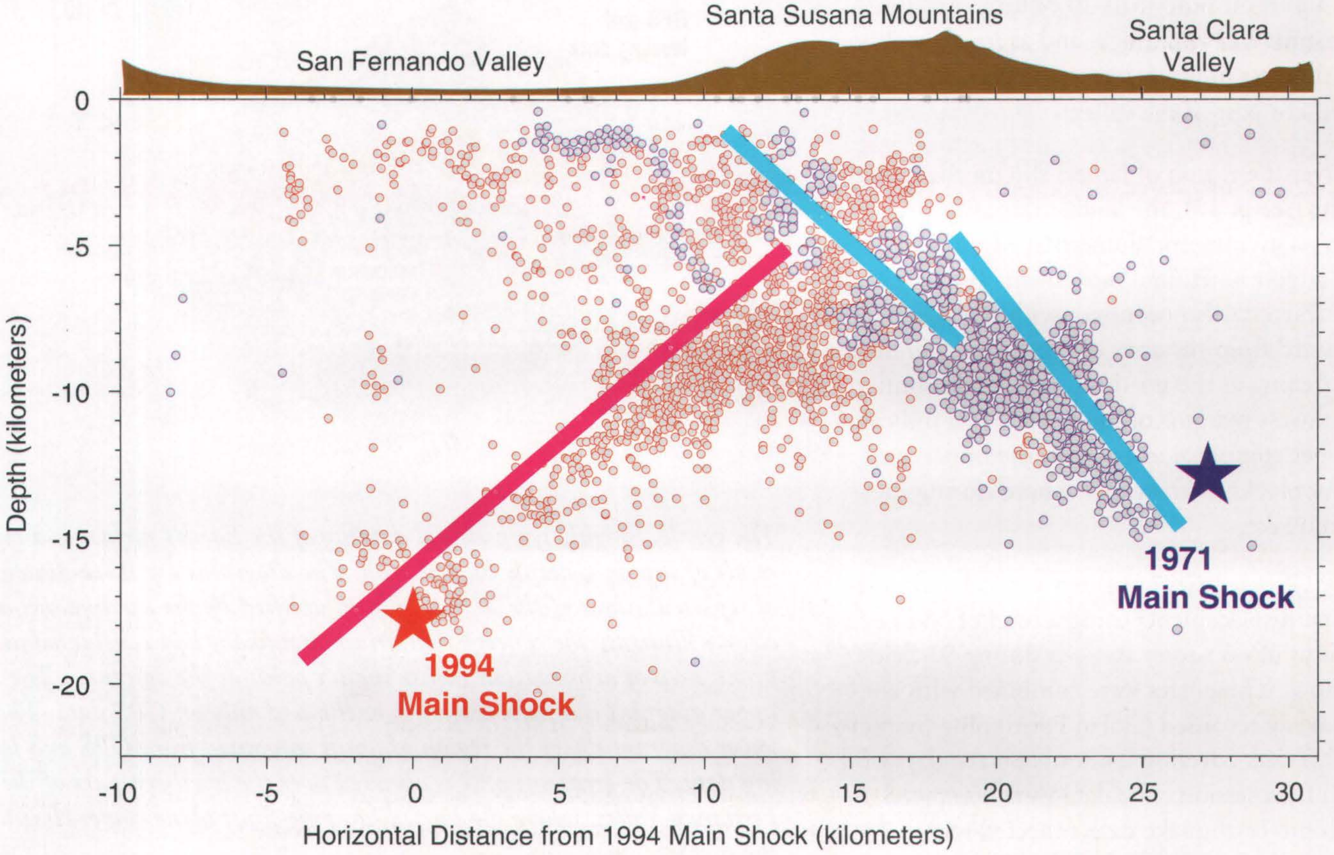


The gentle, roughly symmetrical doming of the Earth's surface is a typical result of slip on a deeply buried fault. The diagrams are three-dimensional representations of the section of land uplifted by the earthquake, and clearly illustrate the concept that an earthquake is best considered as a broad area of deformation rather than a point at the epicenter. The upper diagram is a deformation model based only on GPS data. The lower diagram shows the region of uplift computed from GPS and leveling data. The greatest uplift is centered over the northern part of the San Fernando Valley, where the buried, dipping fault plane comes closest to the surface.

GPS and leveling data and interpretations can be viewed on the WWW at the following Uniform Resource Locator (URL): http://tango.gps.caltech.edu

Describing the Earthquake Source—Estimating Fault Geometry and Slip

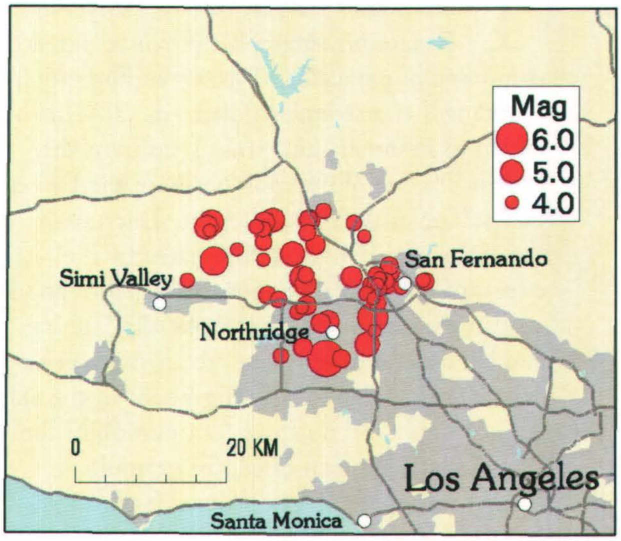
Using strong-motion and displacement data, scientists modeled fault geometry and amount of slip. Modeling suggests that a high-slip area occurred updip and northwest of the main shock hypocenter, and that less than 1 meter of slip occurred in the uppermost 5 kilometers of the crust. This finding is consistent with the lack of clear surface rupture, and with the notion that the intersection with the fault that ruptured in the 1971 San Fernando earthquake formed the upper terminus of slip in the Northridge earthquake. Variations in predicting displacements based on the models indicate, however, that the source geometry is more complicated than a single rectangular plane. ◆



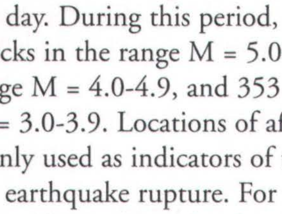
Models of the fault planes of the 1994 Northridge (magenta) and 1971 San Fernando earthquakes (blue) suggest that movement on the buried thrust fault responsible for the Northridge earthquake terminated about 5 kilometers beneath the surface. This movement may have terminated against one of the faults that moved in 1971. Stars show positions of the hypocenters of the two shocks, and the arrays of red and blue dots indicate locations of aftershocks. Compare this illustration with the perspective view on page 13.

Aftershocks

Following the M = 6.7 main shock, thousands of aftershocks occurred in the region of the fault-rupture plane. Aftershocks typically are more numerous immediately following the main shock, and their numbers gradually diminish with time. There were more than 1,000 aftershocks per day during January 1994. By January 1996, aftershocks were still occurring but only at the rate of a few per day. During this period, there were 9 aftershocks in the range M = 5.0-5.9, 42 in the range M = 4.0-4.9, and 353 in the range M = 3.0-3.9. Locations of aftershocks are commonly used as indicators of the areal extent of the earthquake rupture. For the Northridge event, this is shown by the correspondence between the region of aftershocks and the earthquake source areas derived from modeling the fault rupture using strong-motion and geodetic data. ◆



The aftershock zone of the Northridge earthquake illustrates the broad area affected by movements on the fault plane. These are some of the largest aftershocks (M ≥4.0). The largest circle represents the M = 6.7 main shock.

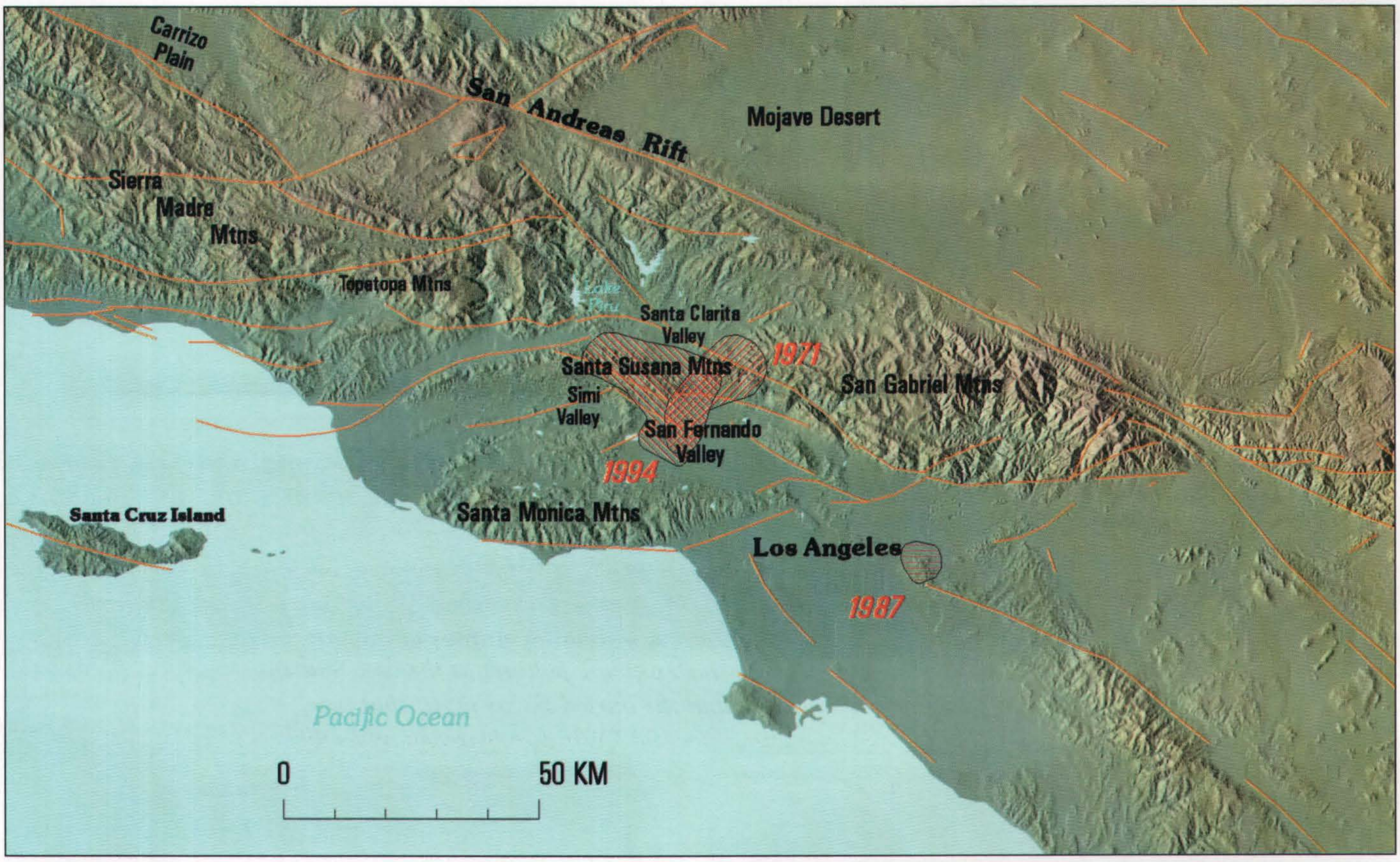


Subsequent work on relocating aftershocks has convinced scientists that the fault geometry is more complicated than either a single uniform-slip dislocation, or distributed slip on a single plane. The rupture almost surely occurred on a more complicated structure that may ultimately be defined by more detailed studies or complex models. The data also suggest that the Northridge earthquake occurred on an eastern extension of the Oak Ridge fault system. There is also a possibility of slip on other faults that might be detected by refinements in modeling. The high-quality seismic and geodetic data will readily lend itself to use in refined models in the future.

The Geological Setting

The San Fernando Valley and adjacent mountains are part of the Transverse Ranges physiographic province that is composed of parallel, east-west trending mountain ranges and sediment-filled valleys. With regard to seismicity and crustal mobility, the province is one of the most active in the United States. The distinctive geological structure of the Transverse Ranges is dominated by the effects of north-south compressive deformation resulting in thrust faulting, strike-slip faulting, and bedrock folding. These are attributable to convergence between the "Big Bend" of the San Andreas fault and northwestern motion of the Pacific Plate, and expressed, for example, in thrust faulting like that exhibited by the Northridge earthquake, the 1971 San Fernando earthquake, and the 1987 Whittier Narrows earthquake.

The western Transverse Ranges are an outstanding example of a geological model of folds and uplifts produced by slip on buried faults. This model is used to help explain the occurrence of earthquakes like the Northridge and Whittier Narrows earthquakes that occurred beneath lowlands many kilometers away from the surface traces of faults that bound nearby mountain ranges. The model has helped identify several major blind thrusts throughout southern California and is being used to postulate the locations of many other buried faults. Investigators then use modern geological and seismological methods to verify the locations and dimensions of these faults. ◆



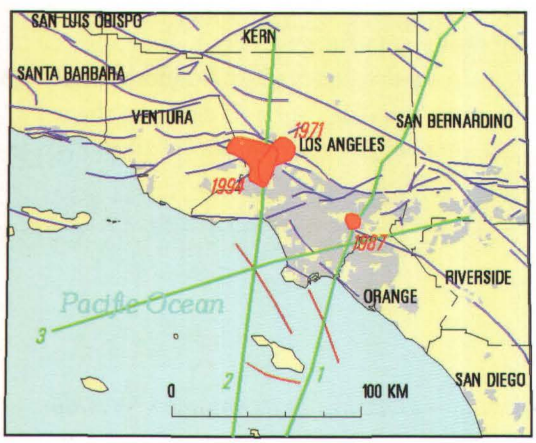
The Transverse Ranges of southern California comprise several east-west trending mountain blocks bounded by major faults and interspersed with broad valleys. The aftershock areas of the 1994 Northridge, 1987 Whittier Narrows, and 1971 San Fernando earthquakes and principal faults are shown for their relations to the physiography.

Images of the Earth's Crust—The Los Angeles Region Seismic Experiment (LARSE)

USGS scientists are attempting to clearly map the crustal structure of the Earth beneath the Los Angeles region, including the subdivision of the crust into blocks, the properties of those blocks, and the nature of the faults that bound them. Scientists are also determining how stress is being applied to this collage of blocks because the faults accumulate strain that most likely will be relieved in the form of earthquakes. Knowing the geometry and interrelations of the blocks, and the stresses being applied, is fundamental to forecasting earthquake scenarios for planning and engineering design.

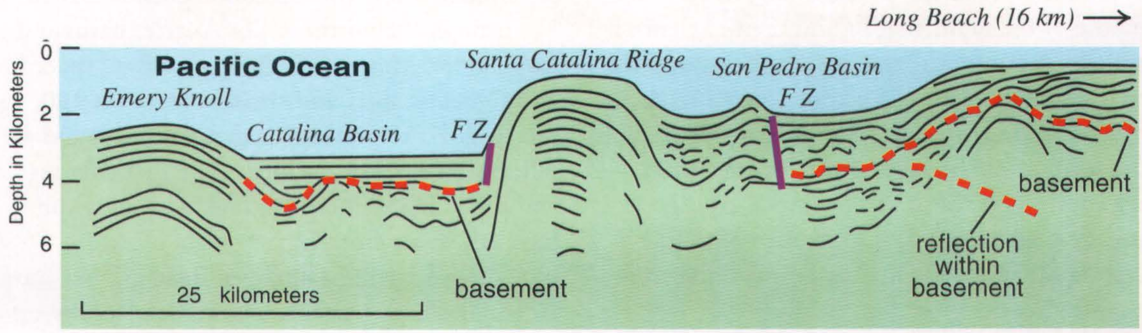
To learn more about crustal structure, the USGS and the Southern California Earthquake Center (SCEC) began a program of seismic imaging known as the Los Angeles Region Seismic Experiment (LARSE). The program began in 1993 and was expanded in 1994 to cover the region of the Northridge earthquake. This experiment was designed to produce reflection and refraction images of the crust along three lines crossing the region, including the offshore environment. Each line represents a massive data-collection system using a few hundred sources and thousands of receivers to produce images of faults and other features to depths of more than 15 kilometers. For example, 640 seismographs assembled from many institutions in North America were used for the experiment along the onshore segment of Line 1. Through the northern Los Angeles basin and San Gabriel Mountains, explosions were spaced 1,000 meters apart and the seismographs 100 meters apart to produce both a reflection and a refraction image of the crust. The first data set and preliminary interpretations available from the LARSE are from Line 1. Data sets from Lines 2 and 3 will be analyzed during 1996 and 1997. The Line 1 data show excellent results with great promise for describing the crustal structure of the Los Angeles region.

The offshore segment of Line 1 targeted the Catalina, San Pedro basin, and Palos Verdes Hills faults. Onshore, principal targets along Line 1 were the top of geologic basement rocks beneath the Los Angeles basin that had never before been imaged. Line 1 was also situated for imaging the blind thrust fault system that caused the 1987 Whittier Narrows earthquake, the Sierra Madre fault system that caused the 1991 Sierra Madre earthquake, and the San Andreas fault.

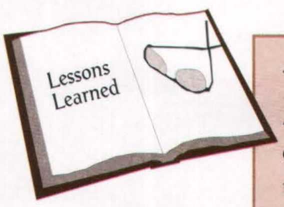


The lines imaged by the LARSE (green) were selected to cross known faults (shown in purple onshore and red offshore) and suspected features, such as buried thrust faults. The lines target such onshore features as the San Andreas fault and the buried thrust faults that produced the 1987 Whittier Narrows and 1994 Northridge earthquakes.

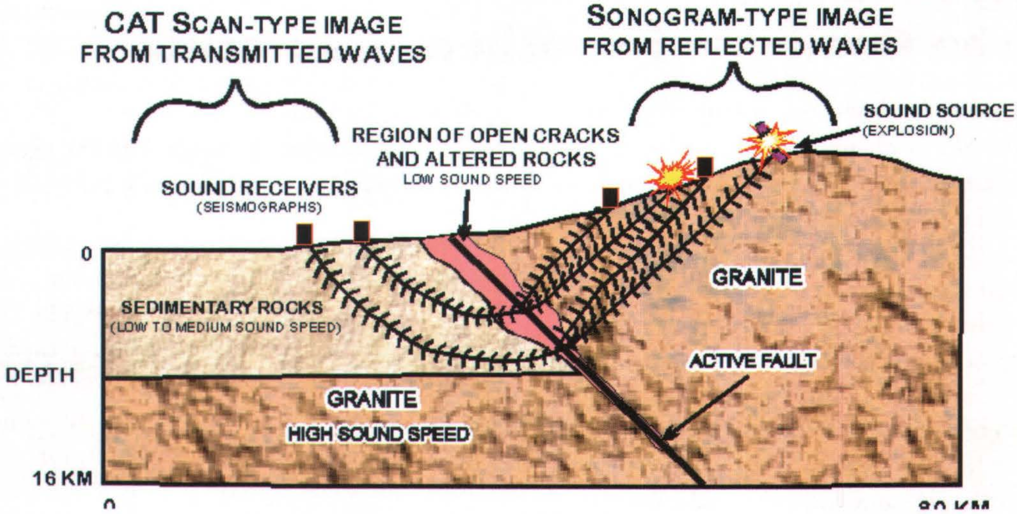
Data from Line 1 show the Catalina and San Pedro basin faults, and evidence of the top of basement rocks beneath the sedimentary and volcanic rocks of the Catalina and San Pedro basins. A possible blind thrust fault offshore shows up as a reflection within basement rocks. An excellent record from near the crest of the San Gabriel Mountains (p. 18; not shown in the accompanying section) shows a prominent reflective zone as shallow as about 22 kilometers. This zone, interpreted to lie chiefly or entirely in the lower crust, almost certainly represents an important change of physical properties, or a "block" boundary within the crust. ◆



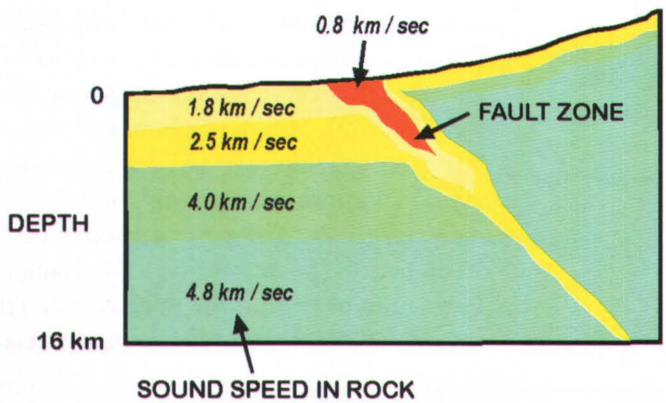
The cross section of the Earth's crust offshore from Los Angeles shows features to a depth of about 6 kilometers. Note the contrast of relatively flat-lying features above basement in the Catalina basin and the heavily distorted features in the San Pedro basin. Reflections within the basement in the eastern part of the section may be evidence of a blind thrust fault. "FZ" indicates known fault zones (see map on p. 19). This image was produced using a sonogram-like technique (see p. 21).



Preliminary images from the LARSE have illuminated many of the structural features originally targeted including offshore faults, basement rocks beneath the Los Angeles basin, and deep crustal structure beneath the San Gabriel Mountains. Given the generally high quality of the data, more refined analysis will likely resolve structures in the upper crust and additional deeper structures. The LARSE data from Line 1 are a promising beginning in defining the various crustal blocks and their bounding faults that make up the tectonic framework that causes the earthquakes in the Los Angeles region.



Using the CAT Scan-like technique, scientists analyze sound and other waves transmitted (or "refracted") through the Earth. Waves traveling more slowly in some directions than in others allow one to outline the shape of regions of slower wave-speed transmission. (In a CAT Scan of the brain, tissue and cavities attenuate X-ray energy differently, and an image of the brain can be constructed using the different patterns of energy transmission.) In the case of a fault in the Earth, waves passing through it are commonly slowed down, and their patterns can be used to delineate the zone surrounding the fault. The zones of low wave speed surrounding faults are believed to be caused in part by tiny open cracks in the rock that are induced by high strain near the faults. Low wave speed can also be caused by chemical effects of circulating ground water that alters the composition of rock in a fault zone.



◀ This CAT Scan-type image shows the characteristics of a fault zone and the adjacent rocks.

Using the sonogram-like technique, scientists piece together faint echoes (the waves reflected from buried rock layers and faults) into a picture of the objects that produced the echoes. (In a sonogram of a pregnant woman, the unborn baby actually reflects sound-wave energy back to the surface of the abdomen, and thus can be imaged.) In some cases, one can see the fault itself. In most cases, however, one can only see the fault indirectly, such as in the offset of one or more layers in the rock cut by the fault. A sonogram-type image is shown on page 20.

Imaging Faults with Seismic Methods

A *fault* is a break in rock along which movement occurs or has occurred. In the upper part of the Earth's crust where rocks are brittle (generally 0-16 kilometers deep), movement occurs on faults in jerks we call ***earthquakes.*** Because earthquake shaking is commonly strongest at points on the Earth's surface closest to the movement on a fault, it is important to get a depiction or ***image*** of faults at depth in order to determine danger zones on the surface. Scientists create images of faults using sound waves generated by explosions or other means at the surface, or by waves from earthquakes. They form images by either of two techniques that can be likened to two medical imaging techniques—"sonograms" and "CAT Scans."

Digital Maps and Databases—Living Electronic Documents on the Geology of Southern California

SCEC Knowledge Transfer, with funding from the National Science Foundation and FEMA, sponsored a 2-day workshop November 9-10, 1995, entitled **"Addressing Seismic Hazards in Southern California: Establishing Dialog Among Academia, the Insurance Industry, and Risk Assessment Professionals."** For information on the workshop, subsequent meetings, and other SCEC activities contact:

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ScecInfo@usc.edu

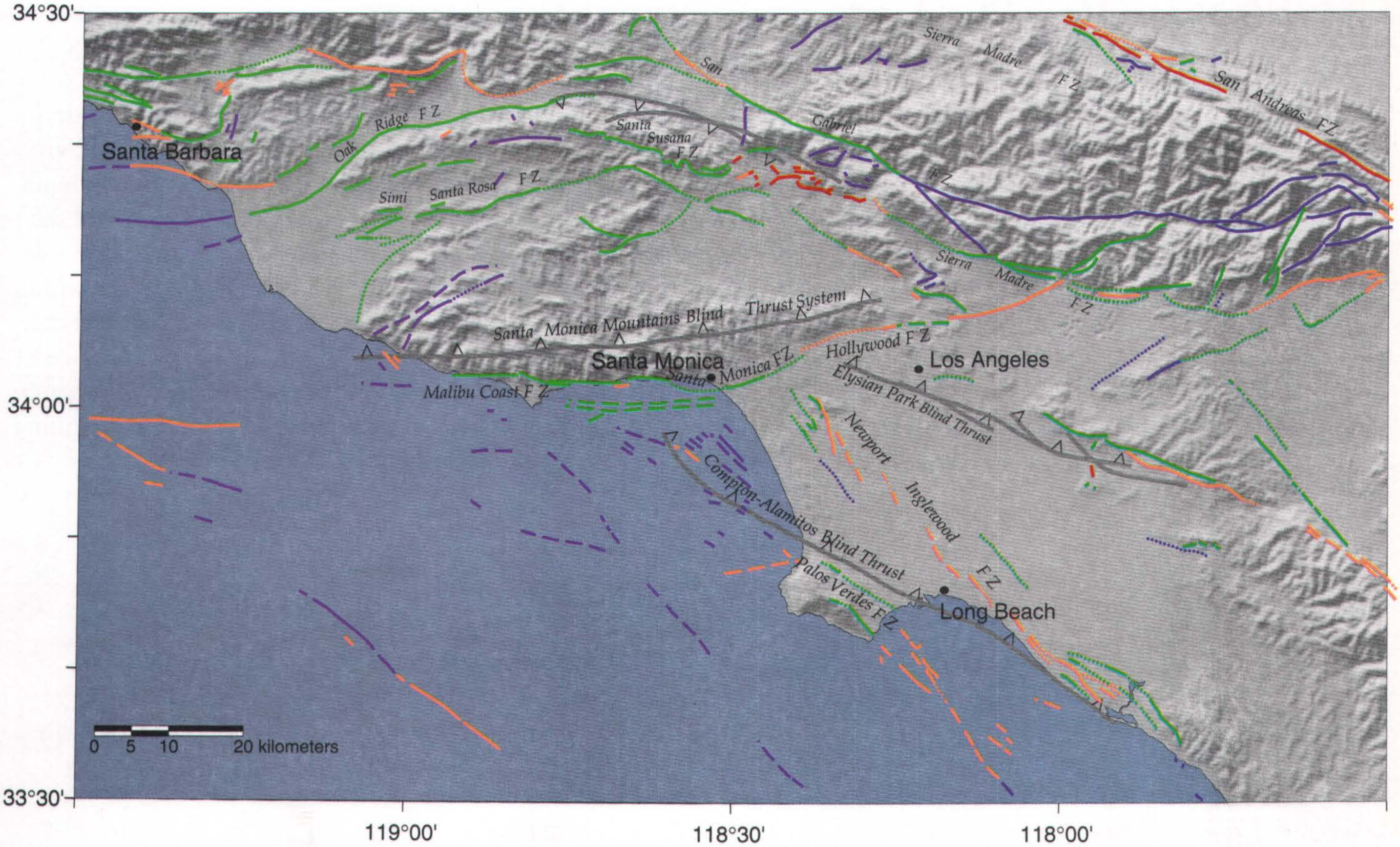
The Northridge earthquake occurred on a concealed, previously unidentified fault directly beneath an urban area. The event thus issued another reminder that, like buried faults, there remain many geological elements that need to be identified to extend our knowledge of the earthquake hazards in southern California. Particular elements within our reach of understanding include the locations of other blind thrust faults. Other such elements are slip rates and earthquake recurrence intervals on major faults that threaten the Los Angeles region, such as thrust faults of the Sierra Madre-Cucamonga system and strike-slip faults of the Newport-Inglewood system.

To help increase geological knowledge and identify deficiencies in geological information, the USGS is compiling special digital information for the region. The information includes a digital map and a database pertaining to the locations and rates of activity of faults and folds in the region. The purposes of this compilation are to (1) evaluate regional seismic hazards; (2) create derivative hazards maps; (3) evaluate the distribution and quality of existing data; and (4) focus on future research. The concept and content of the map and database were developed and refined during meetings with the California Division of Mines and Geology (CDMG) and SCEC in 1994-95. These meetings, culminating in a SCEC-sponsored workshop in March 1995, were convened specifically to confirm the needs of those who would likely be using the map and database in the future. All principals in academia, industry, and government were invited to conceptualize the product and balance its design with the uses they anticipated.

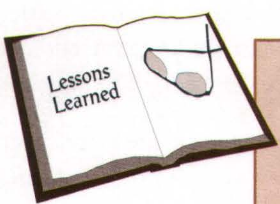
The USGS is taking careful steps to assign systematic quality ratings to information throughout the database. This is especially important in that much information needed for seismic-hazards evaluations typically varies within a range of uncertainty. A specific value used for the database might represent, for example, the value agreed upon by consensus among many investigators, or a value determined from scientific literature. Thus, a database user will need a systematic and explicit reliability rating for the data. The USGS approach will provide database users with enough information to make their own judgments about the quality of evaluations of parameters such as slip rates and other hazards indicators.

For 1995-96, the USGS gave priority to synthesizing and evaluating all fault-related information based on the boundaries of 1:100,000-scale maps for Los Angeles and Long Beach. This information will be available as printed copy and electronically from the World Wide Web (WWW). Future phases of the project will enlarge geographic coverage, and incorporate additional information on folds and the age and deformation of deposits related to concealed faults. The digital map and database are designed to be continually updated through use of the WWW for reviews by users, and corrections and additions by the USGS. Thus, these products will become more comprehensive with time and remain state-of-the-art as long as they are maintained on the WWW for periodic upgrading. ◆

The WWW home page for the digital geologic map and database is currently (1996) under construction. Check the Northridge Earthquake Home Page for linkages: ***http://geohazards.cr.usgs.gov***



The digital fault and fold map for southern California highlights blind thrust systems and other principal faults. Faults exposed at the surface are color-coded according to slip rates and earthquake recurrence intervals, with the red and orange features having higher rates of activity than the green and blue. Specific data on all faults are included in the geologic database.

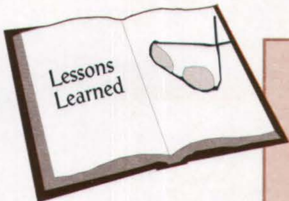


Meaningful earthquake-hazards evaluations need to be based on complete and reliable fault databases. Information users need a good sense of the reliability of the data and maps they will apply to decision making. Having reliability ratings for seismic-hazards information helps increase levels of confidence among decision makers, engineers and others, and helps ensure the most appropriate uses of the information. The USGS and other NEHRP agencies have primary responsibilities for expressing the quality of the information they provide in systematic and explicit terms.

Maps and databases on seismic hazards are more likely to be successfully used if the customers for these products are involved with conceptualizing their design. Additionally, successful use depends upon ready accessibility of maps and information. Using World Wide Web technology allows significant interaction between producers and users of the digital maps and databases, and makes information readily and increasingly accessible as Internet access grows for all.

The Local Effects of Strong Ground Shaking

As in most earthquakes, the patterns of damage that occurred during the Northridge event showed irregular distributions. Generally, the region closest to the earthquake—the northern San Fernando Valley which was directly above the ruptured fault—was shaken most severely and sustained the greatest amount of damage. However, there were also isolated pockets of damage in Sherman Oaks, West Hollywood, Santa Monica, and other distant locations. There are a variety of reasons to explain the more distant damages, such as differences in building construction, effects of ground deformation, liquefaction, and local site amplification. Local site amplifications, or site effects, can result in significant differences in structural damage within the same general area. Understanding and characterizing the site effects are important since areas that demonstrate adverse site effects probably will have amplified ground shaking during future earthquakes. ◆



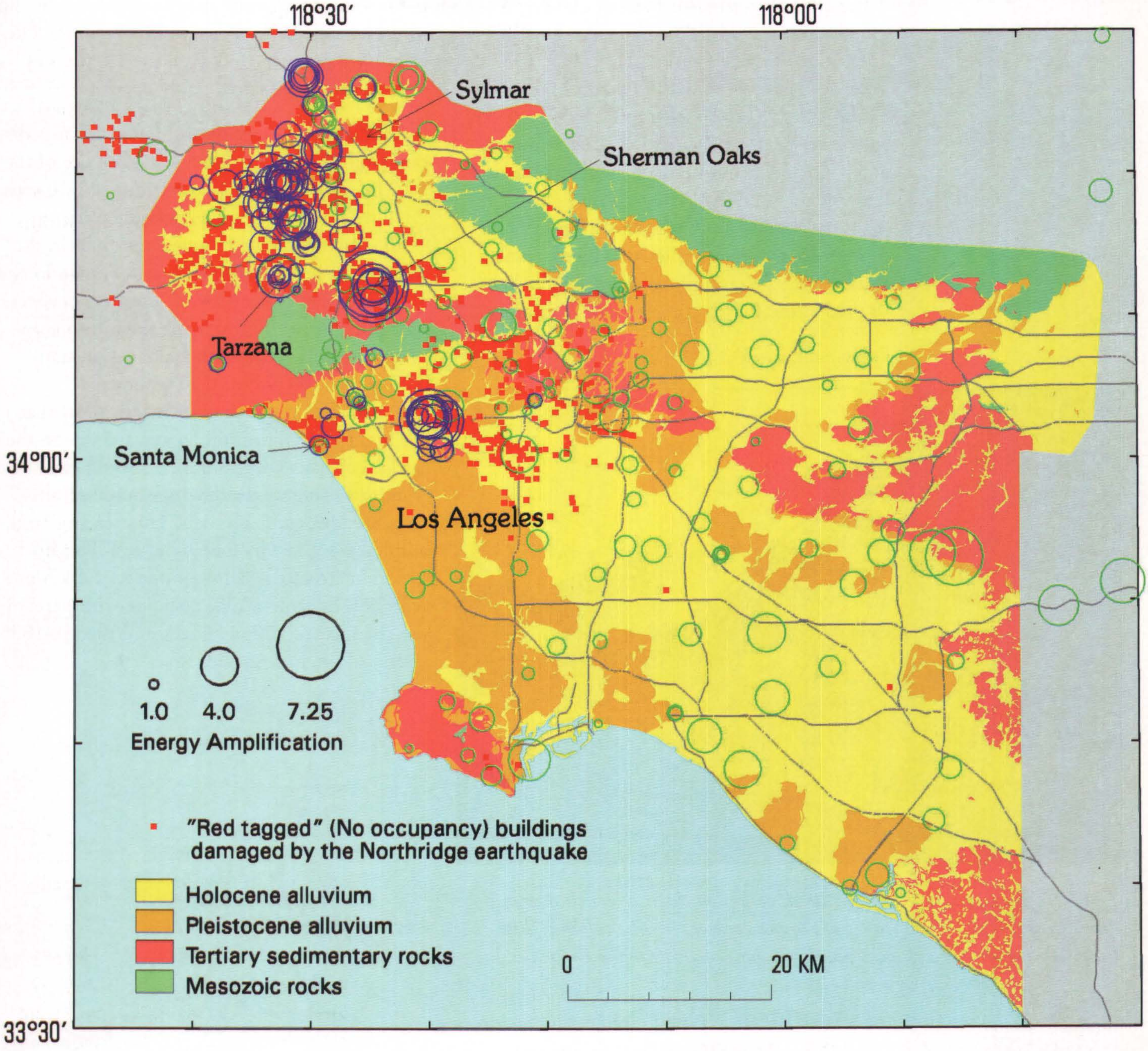
Damage patterns may vary greatly within small areas, and major damages may occur at sites far from the earthquake source. Sometimes this may be due to different types of building construction but, in many cases, the geological characteristics of the site have a large influence on the intensity of the ground shaking. This is the reason that we often see a heavily damaged building at one place while a building of similar construction a block or two away may be completely unaffected.

How and Why Individual Sites Respond Differently to Strong Shaking

The *site-response factor* is the numerical quantity that multiplies the amplitude of a reference wave motion to match the observed ground motion at the site.

USGS scientists initiated several studies to quantify the differences in site responses throughout the Los Angeles region. The initial task was analyzing large volumes of aftershock data (more than 1,300 seismograms from 90 sites, including data from the California Division of Mines and Geology (CDMG) strong motion/instrumentation program) to study site-response issues. The unprecedented database covered variations in site response over widely varying distances, from one city block to an entire sedimentary basin such as the San Fernando Valley. The bulk of the data were collected during portable instrument deployments that targeted many specific areas of severe damage and compared them with minimally damaged or undamaged areas. The deployments also targeted a variety of types of surface rocks, including consolidated and unconsolidated sediments.

Site-response factors at each site were determined for a frequency range of 0.5 to 20 hertz. Generally lower factors (less amplification) were observed for sites in the mountains on firmer rock sites. Higher factors (larger amplification) were observed in the San Fernando and Los Angeles basins, which primarily contain alluvial deposits. There was a good correlation between high factors and the localized areas of severe damage at sites including Sherman Oaks, Northridge, and at the Interstate (I) 10 highway collapses near Santa Monica, and the I-5/State Highway (SH) 14 interchange collapses near Sylmar (see p. 52).



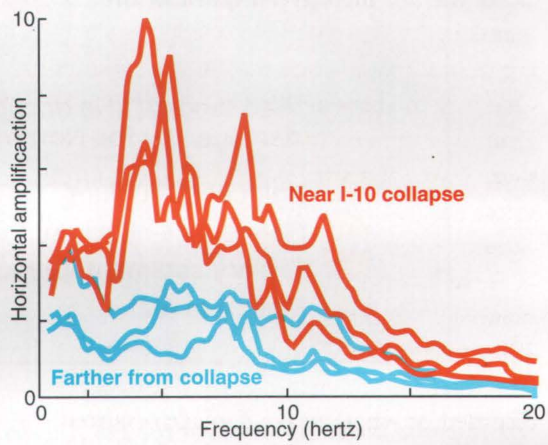
Site-response factors throughout the Los Angeles region demonstrate how shaking varies depending upon the types of geologic materials present. The yellow and orange colors indicate the "softer" materials of sedimentary basins, and the red and green colors represent the harder rocks of hills and mountains. The circles indicate the amplification of earthquake energy in the 2-6 hertz range—the range for which 3- to 5-story buildings are particularly susceptible to the effects of earthquake shaking. Green circles are results from the main shocks of four large earthquakes—the 1971 San Fernando, 1987 Whittier Narrows, 1989 Sierra Madre, and 1994 Northridge events. The blue circles are results from the aftershocks of the Northridge quake. The site-response factor varies as the diameter of the circles, showing that amplifications range up to more than 7 times the reference value of 1.0 for a site on rock. Damage data from the Northridge event (red squares) show the correlation between site-response factors and severe building damage.

In addition to the aftershock data, several hundred records from the main shocks of the 1994 Northridge, 1971 San Fernando, 1987 Whittier Narrows, and 1989 Sierra Madre earthquakes were also used to extend the coverage of site-response estimates. There was generally good agreement between site amplifications determined from the strong-motion data of the main shocks and amplifications from weak-motion data from aftershocks. This agreement validates the practice of using small aftershocks to predict the site response to strong motions.

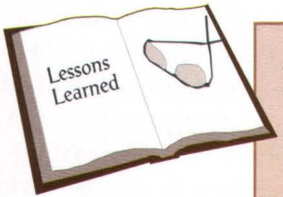
The I-10 freeway at La Cienega Blvd. collapsed despite its distance and direction from the Northridge earthquake epicenter. The collapse illustrates the importance of local amplifications of earthquake energy.

Some of the largest site-amplification factors (up to 7.6) of the 90 sites investigated were obtained in the Sherman Oaks area. However, the site response there was also highly variable on a block-by-block basis. The heavily damaged section of Sherman Oaks is in one of the lowest-lying parts of the San Fernando Valley, contains areas of shallow ground water, and is transected by the Los Angeles River channel. The surficial geology is characterized by unconsolidated sands and gravels. The highly variable pattern in site response may be explained by old meanders in the Los Angeles River that are likely to have produced a complicated pattern of buried, unconsolidated, sandy deposits.

Another area of significant damage that is distant from the epicentral region is the site of the I-10 freeway collapse. Two sections of I-10 separated by about 1 kilometer, sustained damage. Both structures were designed and built in the 1960's and survived the 1971 San Fernando and 1987 Whittier Narrows earthquakes. They were scheduled for retrofit to bring them into compliance with current earthquake design standards when the Northridge earthquake occurred. Site-response calculations show that the highest amplification factors are nearest the bridge collapse, with values decreasing away from this location. To the east-southeast, site-response levels are also high. The trend in large-amplification factors follows an east-west lineation in structural damage for about 4 kilometers. This lineament may coincide with parts of the channels of Ballona Creek and the pre-1825 course of the Los Angeles River. ◆



Horizontal amplifications of shaking at the I-10 bridge collapses in Santa Monica were 3-5 times greater than at sites farther from the collapses. The large amplifications were probably related to the presence of "soft" sediments of the old river channel of the Los Angeles River.



We need not wait until the next major earthquake to further define areas of severe damage potential. There are general correlations between the measured site response and rock or soil types, and good correlations between site response and damage. However, the pattern of site response is characterized by high variability over distances of less than a kilometer. Variations of a factor of 2 were observed over 200 meters, even for the same geologic unit.

Clues from Historical Place Names

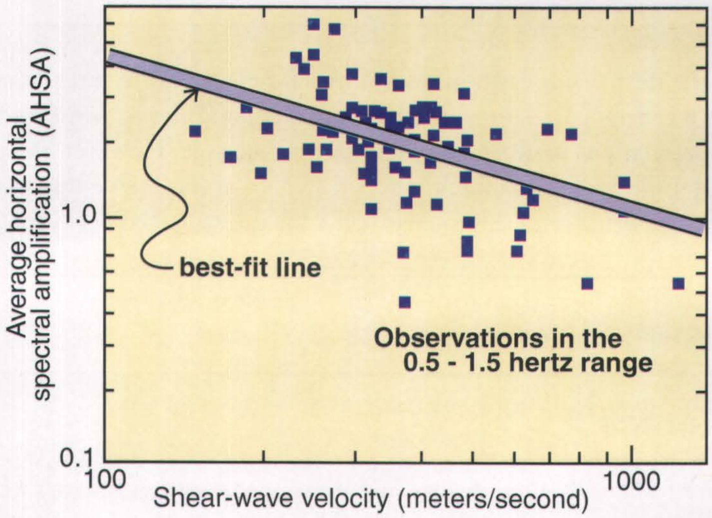
One of the areas that was found to have large site-response factors due to amplifications in soft sediments, was at the collapse of the I-10 freeway at La Cienega Blvd. At present it is difficult to see but, prior to 1825, the Los Angeles River flowed through this location and the surficial geology is composed of sands and gravels from the old river channel. The place name, La Cienega, was given to the area in the 1700's, and in Spanish means "the swamp."

Seismic Shear Waves (S waves) and Site Response

In a simplified view, "softer" geologic conditions at a locality cause larger amplifications of the seismic wave. Thus, the softer sediments in a valley usually exhibit stronger shaking than the hard-rock sites in the mountains. One way to characterize this quality of the ground is to measure the velocity of seismic shear waves at a site. Slower velocities imply softer ground and, therefore, larger site amplifications. In order to made reasonable estimates of these velocities, scientists make measurements in boreholes drilled to depths of about 100 meters. The USGS drilled holes at 12 sites where significant strong ground motions were recorded or where heavy damage occurred. These site-specific borehole data are being used with the strong-motion and damage data to investigate the effects on the geological properties of the sites. Ultimately, this will lead to recommendations for the use of surficial geologic maps to predict site responses in future earthquakes.

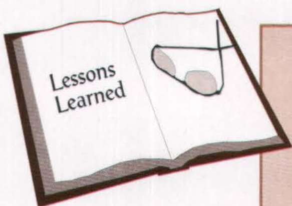
In addition to the borehole measurements, USGS scientists made 11 high-resolution *S*-wave refraction profiles in conjunction with the portable seismograph station sites. These profiles were designed to obtain site information related to heavily damaged regions in Northridge and Sherman Oaks. Also, profiles were acquired in the northern San Fernando Valley to examine the differences in *S*-wave velocities among various geologic deposits mapped on the ground surface. Based on data from the upper 30 meters on the *S*-wave velocity structure, scientists grouped these sites into the four categories shown in the table.

Site location	*S*-wave velocity (meters per second)	Depth range (meters)	Site response
Sherman Oaks:	150	0-10	High
Mid-valley	250	0-10	Moderate to low
North valley	400	0-20	Low
"Rock"	800	0-15	Moderate



USGS scientists confirmed an important correlation between S-wave velocity and ground-motion amplification. The best-fit line for main-shock data for four large southern California earthquakes (blue squares) compares favorably with relations for aftershock data from other earthquakes such as the 1989 Loma Prieta earthquake in northern California. The correlation offers scientists and engineers a tool for predicting site response based on aftershock data.

Although it appears that the high-damage areas can often be correlated with prominent layers of low S-wave velocity, higher damage and stronger shaking also occur with stiffer soils and relatively high S-wave velocities, as observed in Santa Monica. Also, the S-wave profiles in Northridge do not seem to differ enough to account for strong site effects observed in the aftershock data. Calculations using the S-wave profiles give a factor of 2 difference in site amplification, while observed values from aftershock data are as large as 6. These findings indicate that geological structures more than 100 meters deep can play an important role in defining the response at a site. ◆



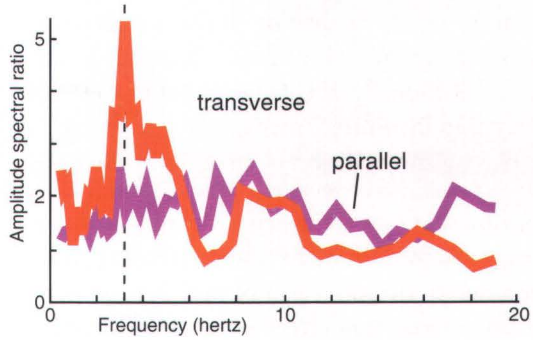
Zones of low shear-wave (S-wave) velocities can generally be associated with amplified ground shaking that caused greater damage. However, simple identification of low S-wave velocities may not be adequate for mapping areas of potentially hazardous site responses. Geological structures more than 100 meters below the surface can be important contributors to site response.

What Happened in Tarzana?

One of the highest accelerations ever recorded during an earthquake occurred at the Cedar Hill Nursery in Tarzana located about 6 kilometers south of the epicenter. The strong-motion record showed a peak acceleration of 1.78*g* (*g* is the acceleration due to gravity) and sustained large amplitudes near 1*g* for about 7-8 seconds. However, much smaller ground accelerations were observed at Encino Reservoir and on Ventura Blvd., each less than 2 kilometers from the Cedar Hill Nursery site. The USGS deployed an array of 21 seismographs to record aftershocks at the site to identify the factors that caused the large motions and to identify reasons for the large differences in ground motions at these three closely spaced sites.

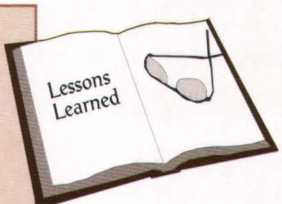
The Cedar Hill Nursery main-shock recording was made atop a hill about 15 meters high, 500 meters long, and 130 meters wide. By comparing aftershock ground motions recorded at the top and base of the hill, scientists observed that the top of the hill shook more strongly than the base. Specifically, the top-to-base amplification ratio was about 2 for motions parallel to the hill (approximately east-west, which is the direction of the 1.78*g* main-shock peak acceleration). For motions perpendicular to the long axis of the hill, the top-to-base amplification ratio was as large as 4.5 for 3.2-hertz motions. Assuming that the hill soils responded linearly during the main shock, the large east-west main-shock motion was amplified by about a factor of 2 due to the topography.

The main-shock accelerations at Cedar Hill Nursery were about 3.5 and 7 times larger than those at the nearby Ventura Blvd. and Encino Reservoir sites, respectively. This discrepancy cannot be fully explained by the differing site geologies and S-wave velocities. Even after considering the surficial geology and the effects of topography, the main-shock motions at Cedar Hill Nursery are about twice what would be expected. These observations show that variations in site geology, topography, and other deeper geological factors caused a factor of 7 difference in accelerations between Tarzana and a site 2 kilometers distant at Encino Reservoir. Such differences make it difficult to make a meaningful contour map of peak acceleration (observed or predicted) for the Los Angeles region without using site geology, at the very least, to guide the placement of contours. ◆



Instruments at the Cedar Hill Nursery in Tarzana recorded significant amplifications of seismic energy that were far greater than those of nearby sites. The amplifications, partly related to the local topography, are about twice what would be expected for similar sites in the Los Angeles region.

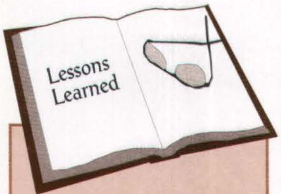
Minor hills can cause substantial topographic amplification. Even though our eyes are drawn to the tallest peaks in a hilly region, for ground motions, the strongest topographic effects may be associated with the smaller wrinkles on the sides of major peaks. Topographic amplifications may occur on most of the hills in the Los Angeles region. These amplifications could be damaging or harmless, depending upon the relative resonance frequencies of the hills and the structures built upon them.



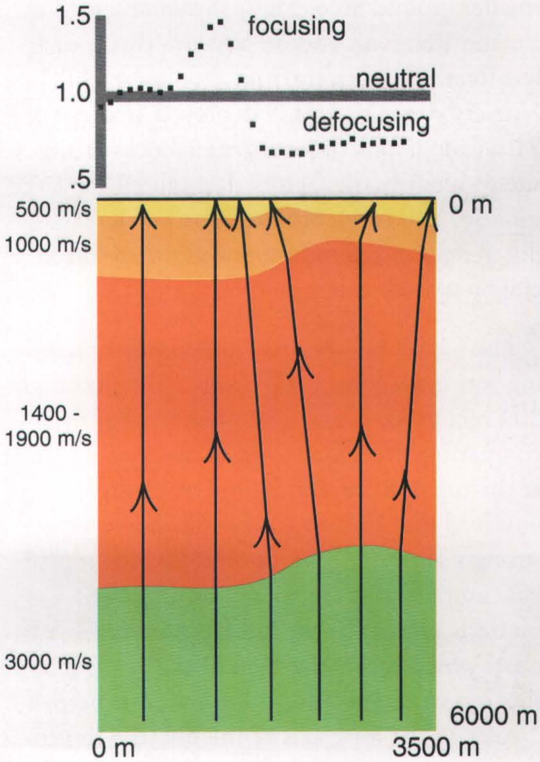
How the Sedimentary Basin Affects Ground Motion in the San Fernando Valley

The effects of sedimentary basins (such as the San Fernando Valley) on seismic waves are more extensive than amplifications and resonances caused by soft alluvium near the surface. Complicated interactions between the structure of the basin and the traveling seismic waves can increase the amplitude and duration of shaking during an earthquake. These interactions can focus the waves from the bottom of the basin, thereby concentrating the intensity of strong shaking in small regions at the surface, while diminishing intensity at other sites. Additionally, the edges of basins can effectively trap incoming seismic waves, thereby increasing the duration of shaking in the basin.

Using small arrays of seismometers over distances of 150-500 meters, scientists determined the velocity and direction of propagation of seismic waves from aftershocks. Even though these data are from small aftershocks, identifying characteristics of the seismic waves is directly applicable to the strong shaking caused by the main shock. A significant finding at one station in Northridge was a large seismic-wave arrival about 10 seconds after the ***direct S-wave***—the principal shear wave that travels directly from the earthquake source to the station. The analysis indicates that this arrival had a relatively slow velocity of about 600 meters per second. This velocity suggests a wave traveling nearly horizontally in the uppermost geological materials—essentially a surface wave. Because of the geometry between the hypocenter and the station, this surface wave cannot have been generated in a standard way by propagation through horizontal layers. Instead, the wave must have been caused by trapping waves near the northern edge of the San Fernando Valley. Analyses of wave amplitudes show that the basin surface wave had amplitudes at 2-4 hertz, as large or larger than the direct S-wave, and increased the duration of shaking for several seconds. Interestingly, scientists found no evidence for large surface waves reflected at the southern edge of the valley. This absence of reflections may be related to the gradual ramp-like shape of that edge.



Surface waves generated by S-wave interactions with basin geometry can increase the duration of shaking for frequencies up to 4 hertz. This phenomenon can apply to earthquakes located outside of sedimentary basins.



A Computer Simulation of "Focusing" and "Defocusing" Effects

Seismic waves traveling upward from depth may be redirected by subtle irregularities at geological interfaces. As waves pass from the deeper unit (green) across the curved interface, their velocity and direction change, then change again in the unit nearest the surface. In this computer simulation, this "focusing" effect produces about 1.5 times the shaking where the waves converge at the surface. "Defocusing" reduces the shaking to about three-quarters of the value for unaffected wave travel.

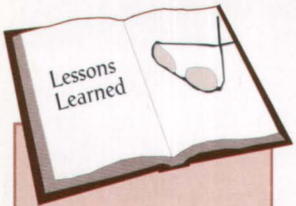
USGS scientists used oil-industry data to provide information about the focusing of seismic waves and effects on strong ground motion. The data consisted of a 4-kilometer profile oriented north-south about 3 kilometers northeast of the Northridge earthquake epicenter. The profile shows a pronounced anticlinal structure (a warping of deeper crustal layers) caused by the Northridge Hills fault. Scientists used the profile and reflection data in a computer simulation to evaluate focusing effects from the buried topography. They assumed that this anticlinal structure was also present at the bottom of the basin. The results showed strikingly large variations in amplitudes of simulated seismograms, with large amplitudes near the middle of the profile. This part of the profile shows a warp in the top of basement rocks—effectively, a "hill" buried by the sediments of the San Fernando Valley. Smaller amplitudes were measured to the north because of defocusing due to the opposite sense of curvature in the "hill" structure. Thus, a 350-meter-high "hill" located about 5 kilometers deep produced factors of 2-3 in amplitude variations over 300 meters at the surface.

The relatively large amplitudes south of the Northridge Hills fault found in the computer simulation correspond approximately to locations of extensive damage in Northridge. Many factors may have played a role in causing this area of concentrated damage, but USGS scientists suggest that focusing from basement topography contributed to the amplified shaking. One characteristic of this focusing is that the amplification is very dependent upon the location of the earthquake source. One would expect less focusing from earthquakes located along strike of the buried topography. Scientists observed such differences in amplification between the damaged and undamaged areas of Sherman Oaks that were dependent upon the direction from the damaged areas to the source of the aftershocks (see p. 25). This suggests that focusing from a deep basin structure could also have contributed to the extensive damage at Sherman Oaks. ◆

Lessons Learned

The curved boundary between a sedimentary basin and underlying hard rock can act as a lens, causing amplification of peak acceleration by 2-3 times over distances of a few hundred meters at the surface. Such focusing likely played a major role in producing the pattern of damage in the San Fernando Valley observed for the Northridge earthquake.

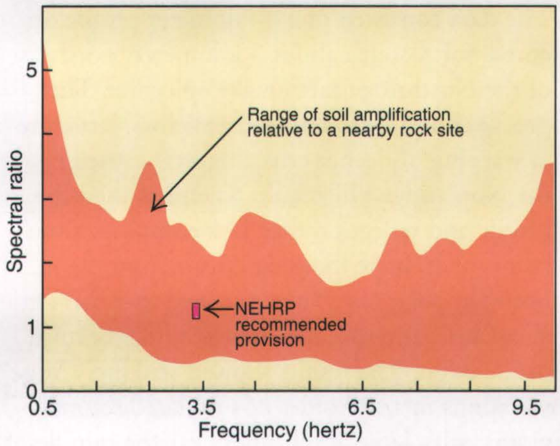
How Soils Respond to Earthquake Shaking



Northridge strong-motion data suggest that the short-period amplification factors as proposed in the 1994 ***NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings*** need to be re-examined. Although there may be some degree of nonlinear soil response, USGS scientists found substantial amplifications (factors of 2 compared with 1.1-1.2 in the NEHRP Provisions) at stiff-soil sites that recorded large accelerations of 0.8-0.9*g*.

Surface soils can be classified in terms of the style of their response to earthquake shaking, and site-response studies seek to determine the degree of "linearity" or "nonlinearity" of the soil response. For a "linear" soil, the observed motions at the surface are amplified proportional to the input ground motion. For "nonlinear" conditions, the soil tends to damp out more of the energy of large amplitude ground motions. Thus, in a large earthquake, nonlinear behavior of a soil will cause less severe shaking than linear behavior. The 1994 edition of the ***NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings***, prepared by the Building Seismic Safety Council (BSSC) for FEMA, includes provisions for the effects of nonlinear soil response. At large accelerations (>0.4*g*), the NEHRP Provisions specify almost no amplification for a stiff-soil site relative to a rock site. At moderate accelerations of 0.3-0.4*g* for periods of 0.3 seconds (3.3 hertz), the provisions call for amplification factors of 1.1-1.2.

The Northridge earthquake provided an opportunity to assess the linearity of stiff-soil sites that experience high levels of ground acceleration. USGS studies examined the relative ground motions at soil and rock sites, with careful comparisons that minimized some of the complicating effects such as rupture directivity (see p. 12) and wave propagation through the complexities of the Earth's crust. Scientists examined the rock/soil differences at a variety of frequencies, producing results that must be considered preliminary until more sites can be studied. However, they found significant amplification for stiff-soil sites for frequencies up to at least 4 hertz, even for input accelerations as high as 0.4*g*. Two soil sites in Sylmar and Simi Valley experienced intense ground accelerations (0.8-0.9*g*) that were much stronger than would be expected if there were significant nonlinear behavior of the soils.



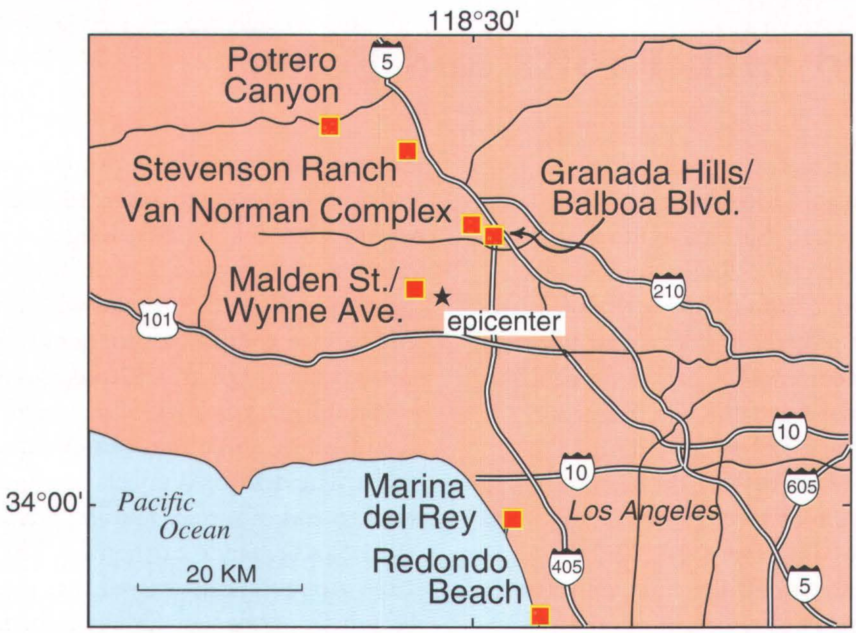
Relative ground motions for rock and soil sites indicate that amplifications during the Northridge earthquake were much higher than those specified in the* NEHRP Recommended Provisions *for nonlinear soil response.

USGS scientists also found one good example of nonlinear behavior at the Joseph P. Jensen Filtration Plant near Sylmar (see p. 43). The data from this site show de-amplification of high-frequency ground motions at a soil site relative to a neighboring rock site. The nonlinear response of the soil near the administration building is consistent with the nearby occurrence of liquefaction during the earthquake. Thus, nonlinear behavior in soft soils can reduce the intensity of shaking at high frequencies. ◆

The Causes and Effects of Liquefaction, Settlements, and Soil Failures

The Northridge earthquake caused numerous ground-surface failures across a broad area of southern California. Failures occurred from the southern parts of Los Angeles County to the Kern County line on the north, and from coastal Ventura County on the west to the southeastern parts of Los Angeles County. These failures included zones of ground fissures and extensional cracking, lateral displacements, settlements with vertical displacements, and compressive deformation in the form of soil and pavement warps and buckles. Such features are common effects of strong earthquakes and warrant scrutiny because of the severe property losses they inflict. USGS investigators focused on documenting the extent and nature of ground failures, analyzing the impacts of ground failures on the built environment, and conducting field investigations to clarify the mechanisms of failure. ◆

Ground failure is used here to describe zones of ground cracking, fissuring, and localized horizontal and vertical permanent ground displacement that can form by a variety of mechanisms on gently sloping valley floors. Landslides and rockfalls that occur on steep hillside slopes are discussed separately beginning on p. 44. In general, ground failure may be caused by (1) surface rupture along faults, either as a primary rupture on the ***seismogenic*** fault or as a ***sympathetic rupture***; (2) ***secondary*** movement on shallow faults; (3) shaking-induced compaction of natural deposits in sedimentary basins and river valleys, or artificial fills; and (4) liquefaction of loose sandy sediment.



Although ground failures were scattered throughout the Los Angeles region, most occurred near the epicenter and above the fault-rupture plane (see p. 13). Failures in artificial fills occurred up to 57 kilometers from the epicenter. USGS scientists investigated several areas in great detail to understand the mechanisms of the failures.

Earthquakes and Ground Failures

When large faults rupture and produce earthquakes, they generally deform the ground surface. Primary surface faulting, such as the 22-kilometer-long surface rupture associated with the 1971 San Fernando earthquake, is the direct effect of movement on a ***seismogenic***, or earthquake-producing fault. Rupture on nearby faults induced by the primary event (***sympathetic rupture***) may also produce surface faulting. Earthquakes can also produce ***secondary*** features that look similar to primary surface rupture. Primary features related to known or suspected faults can be readily studied by geologists and directly linked with earthquake activity on those faults, while secondary features may be difficult to link to activity on a particular fault. However, studies of secondary features can provide information on the effects of earthquake shaking at selected sites—extremely important information for seismic-hazards evaluation that cannot be directly obtained from studying seismogenic faults alone.

Failures Associated with Faults and Folds

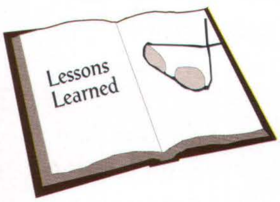
No evidence of primary surface rupture associated with the seismogenic fault was found. Surface ruptures at Potrero Canyon and Stevenson Ranch were located along the hinge of a fold near where the seismogenic fault projects to the ground surface, but neither occurrence appears to be associated with the seismogenic fault. The Stevenson Ranch ruptures, a 320-meter-long zone of bedding-plane faulting that displaced building pads a maximum of 19 centimeters, appear to be related to folding above the blind thrust fault. In contrast, trenching and strain studies of the 3-kilometer-long belt of ground cracks that formed within Potrero Canyon indicate that they are shallow features formed in sediments along the margins of the valley. Trenching studies indicated mechanisms of shallow failure by shaking rather than by secondary tectonic deformation.

The most extensive belt of 1994 ground failures overlies the Mission Hills fault zone in the Granada Hills-Mission Hills area. Ground cracks displaced the foundations of houses, fractured swimming pools, broke apart sidewalks and streets, and ruptured utility lines within a belt 5 kilometers long and several hundred meters wide. The deformation was concentrated in certain areas within the belt and formed complex associations of ground and pavement cracks, settlements, compressional features such as buckled pavement and tented sidewalks, and offsets of sidewalks and curbs. The deformation belt nearly abuts the western end of surface faulting produced by the 1971 San Fernando earthquake. The area of 1994 ground cracks showed that there had been little permanent surface deformation during the 1971 earthquake; however, some minor cracks were reopened in 1994.

The most intensive ground deformation and damage in the Granada Hills-Mission Hills area occurred near Balboa Blvd., where several zones of tension cracks and a zone of compression (expressed as crumpled pipelines and crushed pavement) formed in fine-grained alluvium. USGS mapping, trenching, and strain studies in this region showed that the ground shifted downslope as much as 50 centimeters between the zones of ground extension and compression, and that the ruptures were shallow features consistent with shaking-induced ground failure.

Subsurface investigations also revealed evidence for a near-surface fault at the southern margin of the deformation zone near Balboa Blvd. This strand of the Mission Hills fault zone apparently was not active during the earthquake, nor does it appear to have been significantly active in the last 10,000 years. It appears to localize ground failure by acting as a ground-water dam in the Balboa Blvd. area. To the east, several zones of ground cracks that coincide with stream courses filled for housing developments also lie along the fault, as do linear zones of tension cracks that are observed in bedrock in the Mission Hills. The bedrock cracks are probably from minor landslide movement, although the possibility of fold-related secondary faulting cannot be ruled out entirely. ◆

This view, taken the morning of the earthquake, looks west across Balboa Blvd. A zone of extensional ground failure runs approximately from the upper left to the lower right corners of the photograph. Ground failures ruptured two major water lines and two gas lines beneath the street. Several minutes after the earthquake, a spark from the pickup truck (center) ignited leaking natural gas, and produced a fireball that burned five houses to the ground and seriously damaged a sixth.

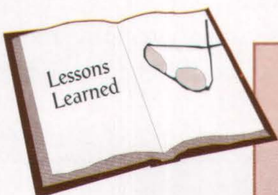


Faults and fold axes appear to be important in localizing ground failure, although the mechanisms that cause ground failure near fault zones can vary. Some secondary tectonic movement associated with folding above the blind thrust may have occurred locally, but the effects of these failures are minimal.

Cracking in Natural Ground

Within the San Fernando Valley, ground cracks that resembled liquefaction-related lateral spreads and settlements were widespread. Liquefaction could not be confirmed, however, because sand did not vent to the surface. Failures in nonliquefied areas commonly were underlain by both fine-grained sediments (silt and clay) and ground water at depths of less than 10 meters. USGS scientists studied two sites in detail—Malden St. and Wynne Ave.. Near Malden St., a 500-meter-long by 20-meter-wide zone of tension cracks and settlements broke sewers and water pipelines and damaged the foundations of several homes, streets, curbs, and utilities. Curbs and gutters were displaced 6-10 centimeters, and maximum vertical settlement was about 20 centimeters. At its east end, the Malden St. zone trended northwesterly and expressed a right-lateral displacement in curbs amounting to about 17 centimeters. The failures were shallow and resulted from downslope movement of nearly 30 centimeters, consistent with shaking-induced mechanisms of ground failure. Ground failure at the Wynne Ave. site ruptured both water and sewer lines, and consisted of a zone of settlement about 150 meters long and 12 meters wide. Permanent vertical offset across cracks ranged from 10 to 20 centimeters. ◆

This ground crack is typical of features found by USGS geologists in many areas of the San Fernando Valley. The cracks damage buildings and streets at the surface, and fracture water, sewer, and gas pipes underground.

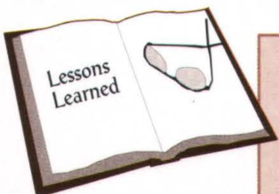


The Northridge earthquake produced widespread ground failures in areas of the San Fernando Valley underlain by both ground water and fine-grained sediment (silt and clay) at depths of less than 10 meters. This empirical association provides a broader basis for identifying areas subject to ground-failure hazards than by using liquefaction susceptibility. The association of materials and ground-water depths can be used to identify general areas where site-specific studies of potential ground failure may be advisable.

Fill Failures

The most widely distributed ground failures appear to be associated with areas of filled land. Some occurrences were clearly the result of liquefaction, while others lacked direct evidence for liquefaction. In nearly all cases, however, depth to ground water was less than 10 meters, and any associated natural deposits were geologically recent.

Fill failures in the San Fernando Valley occurred along the channelized course of Bull Creek, which at many localities had been filled for development. Settlements at John F. Kennedy High School and on Odessa Ave. north of Rinaldi St., caused significant damage to structures and buried utilities. Several streets near the epicentral area exhibited settlement and cracking over known storm drains, and other streets nearby may have been located over old filled drainages. A small number of ground failures occurred along the Pacific Coast from Santa Monica to the Port of Los Angeles. These were mainly associated with poorly compacted sandy fills north of the Santa Monica Pier and near Marina Del Rey. In Redondo Beach, a quay wall moved more than 5 meters laterally due to liquefaction. Overall, however, ground failure in the coastal areas was modest. Ground failure concentrated in the southeastern portion of Simi Valley also could be traced to failure of fills, especially fills placed along Simi Arroyo and along the former courses of its tributaries. Ground failures commonly appeared to involve cracking and differential settlement of fills and occasional liquefaction in underlying alluvial deposits. The failures caused significant damage to structures and buried utilities. ◆



Poor performance of loose fills continues to pose risks to the built environment. In the Northridge earthquake, liquefaction in areas of shallow ground water contributed to many fill failures. Areas of filled land need to be identified and characterized to determine the likelihood of failure during future earthquakes.

Ground Failure and the Built Environment

To evaluate the impact of ground failures, USGS investigators compiled specific locations and descriptions of damage for more than 7,100 structures, 200 leaks in water-distribution lines, and more than 2,000 significant breaks in sewer lines within a 24-square-kilometer area of Granada Hills-Mission Hills. This compilation was merged with detailed mapping of ground failure in the heavily damaged region near Balboa Blvd. ◆

Damage to Underground Utilities

Leaks in water-distribution lines were concentrated within the 5-kilometer-long zone of ground cracks in the Granada Hills area. More than 45 leaks per square kilometer occurred in this zone. Near Balboa Blvd., pipe failures exceeded 200 per square kilometer. In contrast, pipe leaks occurred randomly at a rate of about 4.3 per square kilometer outside the ground-failure zone. Specific locations of pipe leaks closely match the zones of ground failures, suggesting that water lines tended to break primarily where the ground fractured. The few failures outside the areas of ground cracking are mainly attributable to corrosion in old pipes, or to poor welds.

With FEMA funding, the City of Los Angeles has visually assessed, via closed-circuit television, nearly all of the approximately 275 kilometers of sewer mains within the USGS study area. Sewer pipes are made of extremely brittle vitreous clay, buried at depths of 1.5-4 meters, and are highly susceptible to structural damage. About 10-20,000 structural defects were observed in pipes within the study area, but most of these were very slight offsets or minor cracks at joints between pipe sections. These defects are attributable to flexing or pounding at the joints during the earthquake; however, the defects may have been produced during prior earthquakes, or during construction and subsequent settlement around the pipes. The more than 2,000 severe sewer defects that might require repair or replacement, such as cracked and broken joints, joint offsets, and holes or fractures in pipe sections, predominantly occurred within ground-failure zones. In areas outside these zones, 55 significant defects occurred per square kilometer, whereas they rose to more than 295 per square kilometer within the ground-failure zone and to more than 1,150 per square kilometer near Balboa Blvd. Generally, extensional and compressional failures in the sewer lines corresponded closely with earthquake-induced north-south extension and compression of the land surface. ◆

Ground failure, rather than ground shaking, is the principal cause of damage to water and sewer lines. The brittle sewer pipes tended to fail under much lower strains than water lines, so damage to sewer lines is considerably more extensive. Identifying where and to what degree subgrade utilities are at risk from earthquakes can be accomplished by accurately delineating regions at risk of ground failure during earthquake shaking.

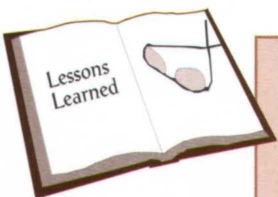
The National Institute of Standards and Technology (NIST) has the lead role in developing a plan for the Federal role in the performance of lifelines. The Federal Emergency Management Agency (FEMA), following the Northridge earthquake, funded the American Society of Civil Engineers (ASCE) to develop standards for earthquake-actuated shut-off valves for natural gas lines. Such valves would reduce the threat of fire following an earthquake.

Structural Damage Due to Ground Failure

To investigate the potential significance of ground failure to structural damage, the USGS examined damage records for single-family residences situated on geologically recent sediments. Information on costs and types of repairs for damaged homes was compiled from safety inspections made shortly after the earthquake, and from records of building permits issued for earthquake repairs. Such records were available for about one-half the total building stock in the study area. Other properties either suffered no reportable earthquake damage, were repaired without permits, or had not been repaired during the study period.

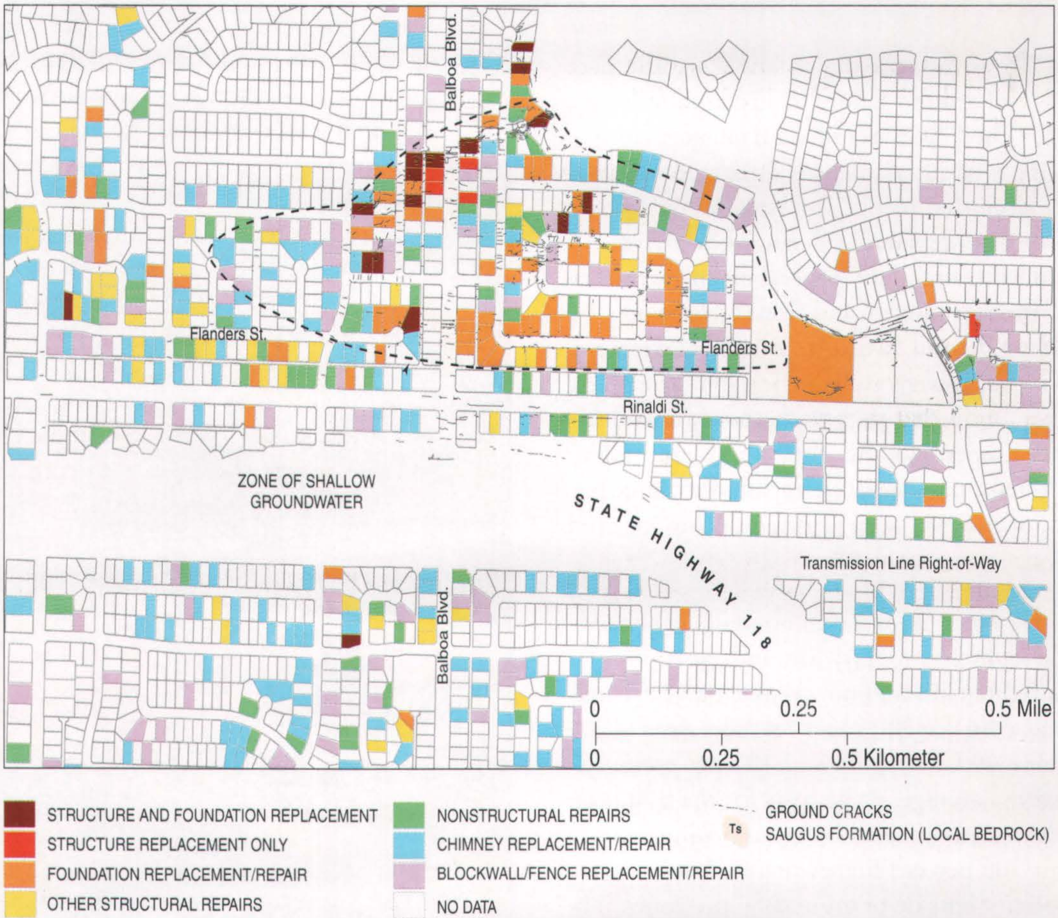
In the study area, 4,829 homes experienced some reported property loss and the kinds of required repairs are known for 2,983 of them. Repair costs for all properties range from $200 to $381,000, averaging $12,193 per property. However, average repair costs for the 315 properties in areas affected by ground failure were about 300 percent higher than for the 4,514 properties outside of ground-failure zones. The higher costs in ground-failure zones were largely due to major foundation repairs, and demolition and replacement of buildings where foundations were also damaged. Furthermore, most structures that experienced significant losses were typically located on or near zones of mapped ground cracks. ◆

The foundation slab of this 1-story single-family home in the Balboa Blvd. area was damaged by small settlement and extensional ground cracking that is evident in the lawn (arrow, foreground). Structural damage to the foundation was so extensive that the home had to be demolished.

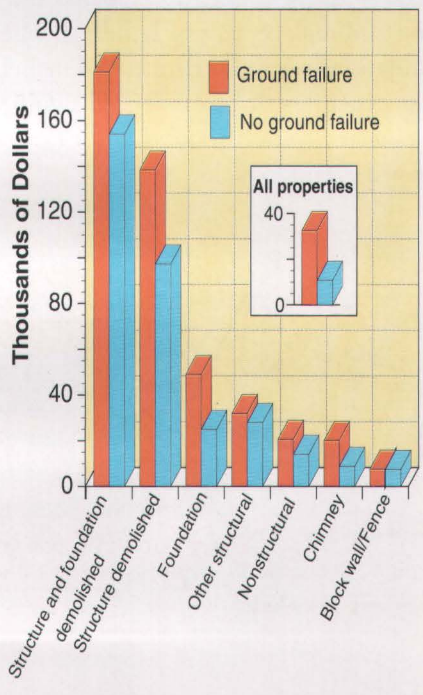


Significant losses to single-family homes in ground-failure areas appear directly attributable to the ground failure itself. Had the Granada Hills-Mission Hills area not been subject to ground failure in the Northridge earthquake, the resulting damage to structures in that area would likely not have been much greater than for the northern San Fernando Valley as a whole. These results emphasize the importance of the ground-failure hazard for future mitigation and research strategies.

Earthquake repair data for the Balboa Blvd. area show repairs relative to the zones of ground-failure cracks and the shallow ground water mapped by USGS scientists. Most property loss is coincident with these zones.



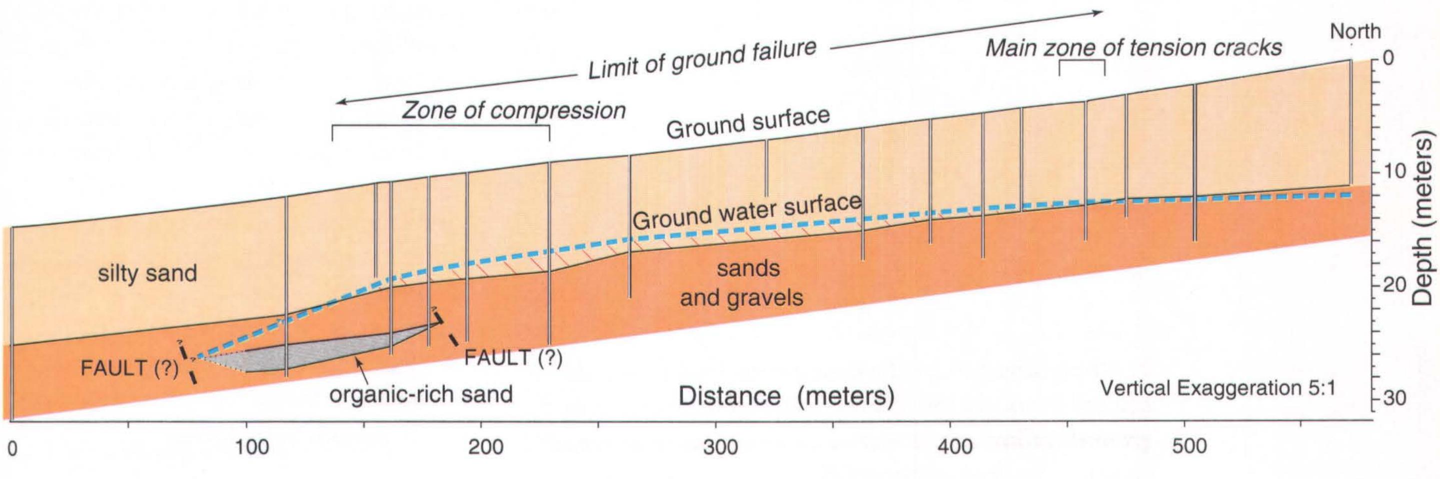
This chart shows the average repair costs for single-family structures within and outside of ground-failure zones, also subdivided by type of required repair. Properties within ground-failure zones suffered nearly three times more damage (reflected by repair cost), on average, than houses unaffected by ground failure. The damage within ground-failure zones is distinctly different from damage outside these zones: foundation damage, which is nearly six times more prevalent within ground-failure zones, and twice as expensive to repair accounts for most of the additional losses.



How Does Ground Failure Occur?

USGS scientists evaluated two alternate mechanisms of localized soil failure and secondary tectonic deformation. Extensive investigations of geotechnical properties of the soils were carried out at three sites at Balboa Blvd., Malden St. and Wynne Ave. These consisted of borings to determine the geologic structure and cone-penetration tests to estimate the soil strengths. All three sites were also in areas of gently sloping ground, and scientists found that they were underlain by saturated soils that could be expected to fail when subjected to high levels of ground shaking. Therefore, localized failure in a buried layer was thought to be the mechanism causing the failure at the surface. However, it was not clear that the failures could have been anticipated even if detailed subsurface investigations had been conducted before the earthquake. Two of the sites, Balboa Blvd. and Wynne Ave., were underlain by saturated sands that were predicted to liquefy at the levels of ground shaking recorded in the epicentral region. However, the cracking at Malden St. is suspected to have been caused by a different mechanism than liquefaction, probably dynamic shear in weak clay. This mechanism should be more seriously considered in areas underlain by weak soils which may be subjected to high levels of ground shaking.

Secondary tectonic deformation could possibly explain some of the 1994 ground failures at Balboa Blvd. and Wynne Ave., but USGS scientists consider it unlikely. The stratigraphic complexity and an abrupt change in the depth to ground water at the south end of the Balboa Blvd. study area suggests the presence of a tectonic fault. However, the fault does not appear to have significant recent movement, and the 1994 ground-failure zone extends almost 300 meters to the north where no stratigraphic evidence exists for faulting. The 2-meter step on the top of the sediment observed at Wynne Ave. may have contributed to the location of the ground failure there. ◆



A cross section at the Balboa Blvd. site illustrates the conditions of silty sands and ground-water levels at depths of less than 10 meters that caused liquefaction in the area. Note the influence of the faults on the configuration of the ground-water surface. Numerous boreholes (vertical lines) were used to map and identify geological and hydrological characteristics of the section.

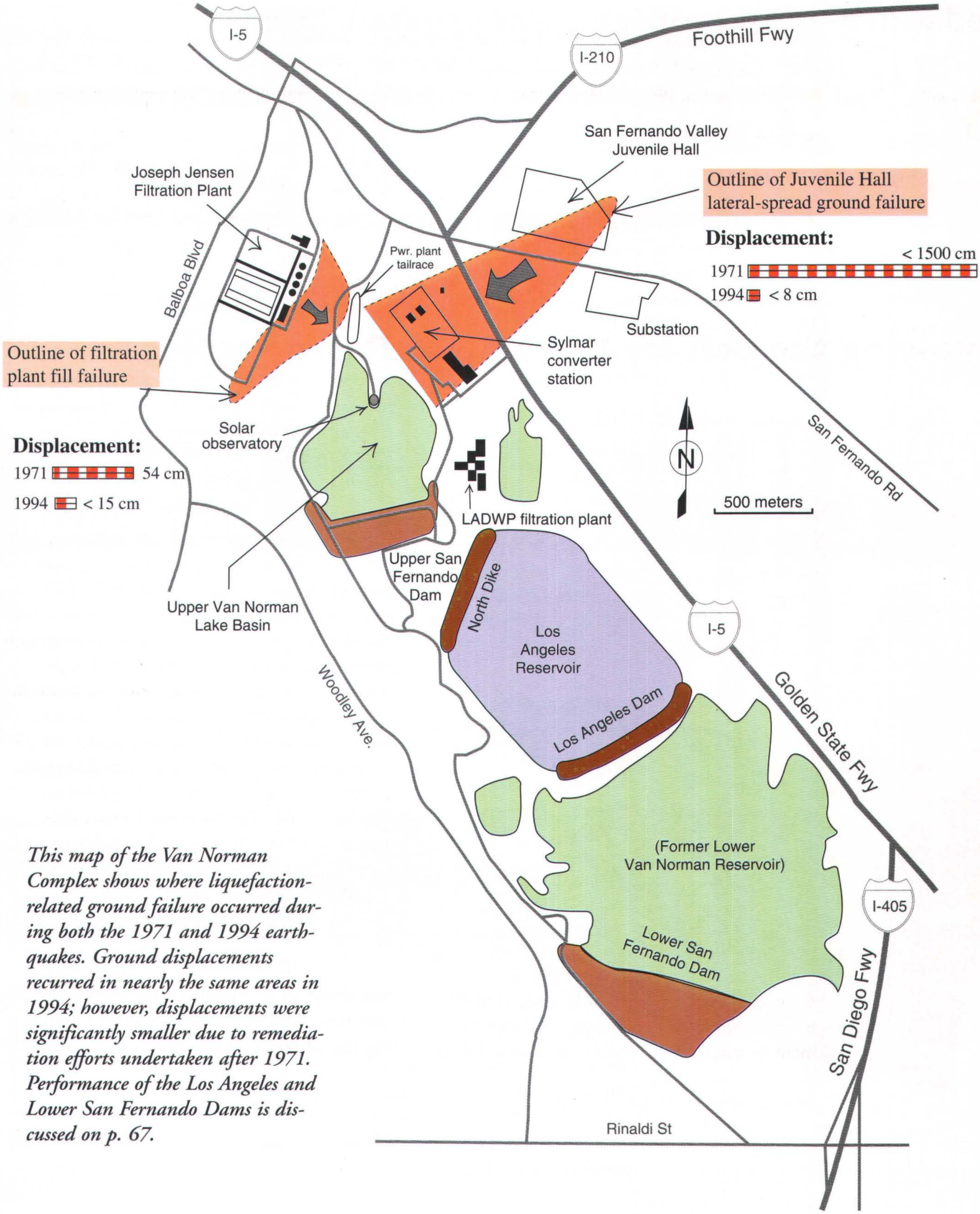
General areas susceptible to ground failure can be delineated on the basis of ground-water levels and geologic materials of the surface and subsurface. However, it may be difficult to adequately map the subsurface structure to predict the distribution of ground failure in future earthquakes. Furthermore, scientists have many tools to predict areas subject to ground failures caused by liquefaction, but predicting specific problem locations will continue to be challenging. The Northridge earthquake showed, for example, that very strong shaking directly beneath weak soil sites may cause failures by mechanisms other than liquefaction.

Improving the Soil for Earthquake Resistance

The Northridge earthquake also showed that losses can be reduced by locally increasing the strength of soil through ground improvement. The Van Norman Complex lies within an area badly damaged by liquefaction-related ground failure during the 1971 San Fernando earthquake. After 1971, attempts were made to improve soils in parts of the area because the complex contains several major lifelines and key facilities serving the vast metropolitan areas to the south. These include major water conveyance, storage, and treatment facilities; electrical generation and transmission facilities; a solar observatory, a juvenile correctional facility, fuel pipelines, rail lines, and highways (I-5, I-210, I-405, SH-14, and SH-118). Although the Northridge earthquake produced localized ground failures that damaged a number of facilities, the overall damage was significantly less than in the 1971 earthquake, despite higher levels of ground shaking in 1994.

The areas of the Joseph Jensen Filtration Plant and the San Fernando Juvenile Hall illustrate the positive aspects of ground improvement in reducing the severity of ground failure. In 1971, up to 2 meters of ground displacement damaged Juvenile Hall buildings so severely that they were razed and eventually replaced. The site was excavated to a depth of about 12 meters and reconstructed with a compacted buttress fill.

Investigation after the Northridge event revealed that some parts of the 1971 failure zone failed again, but the magnitude of displacement was small enough (less than 8 centimeters) to suggest that remediation measures were nearly entirely successful. The Joseph Jensen Filtration Plant was under construction on an engineered fill when the 1971 quake struck. Liquefaction in alluvium under the fill produced about 0.5 meters of lateral displacement at the main control building, and displacement increased to about 1 meter near Upper Van Norman Lake. Remedial measures since 1971 included installation of at least 1,100 gravel columns, placed as conduits for ground water in an effort to mitigate liquefaction. The cumulative width of extensional failures in the fill measured after the 1994 quake was about 15 centimeters, suggesting considerable success of the remedial efforts in minimizing the effects of liquefaction. ◆

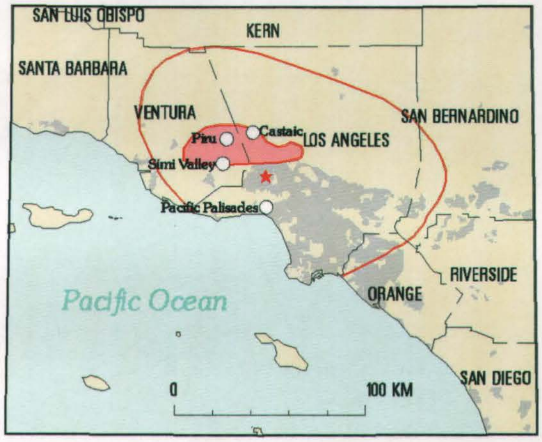


This map of the Van Norman Complex shows where liquefaction-related ground failure occurred during both the 1971 and 1994 earthquakes. Ground displacements recurred in nearly the same areas in 1994; however, displacements were significantly smaller due to remediation efforts undertaken after 1971. Performance of the Los Angeles and Lower San Fernando Dams is discussed on p. 67.

Landslides—Common and Unexpected Effects

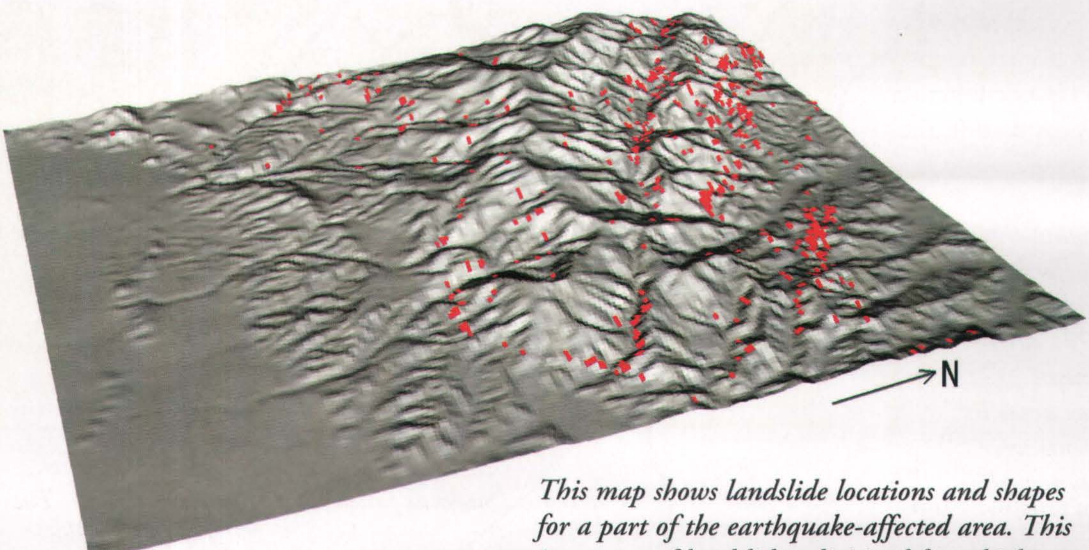
The earthquake caused tens of thousands of landslides over an area of 10,000 square kilometers. The landslides destroyed dozens of homes, blocked roads, disrupted pipe and powerlines, and blocked streams. They also generated massive clouds of dust, precipitating an epidemic of ***valley fever*** that caused three fatalities. While widespread and abundant throughout the region, landslides were most concentrated in the Santa Susana Mountains immediately north of the San Fernando Valley, and in the mountains farther north in the vicinity of Piru.

Scientists from the USGS arrived in southern California on the day of the earthquake and worked for several weeks documenting the extent and effects of landslides, and evaluating the continuing hazards they might pose. The USGS mapped the precise locations and shapes of more than 11,000 individual landslides using extensive fieldwork and high-resolution aerial photography taken by the U.S. Air Force on the day of the earthquake.



Location of highest concentration of landslides (shaded area) and maximum extent of landsliding (red line) resulting from the 1994 Northridge earthquake (star).

The areas of greatest landslide concentration occurred in weak, poorly cemented, geologically young rock and soil. These materials have been rapidly uplifted through the eons by events like the Northridge earthquake, and because of their weakness are rapidly eroded by rainfall, earthquake shaking, and other processes. The balance of rapid uplift and erosion in these weak materials has produced steep-walled canyons with high topographic relief, and slopes that fail readily during earthquakes and rainstorms.



This map shows landslide locations and shapes for a part of the earthquake-affected area. This inventory of landslides, digitized from high-resolution aerial photography, is the basis for making a predictive model of future seismic landslide hazards.

The most common types of landslides were shallow rock falls and rock slides, numbering in the thousands, and up to tens of thousands if very small failures are counted. These landslides were highly disrupted, chaotic jumbles of soil, rock, and vegetal debris. In some areas, more than 75 percent of slope areas were denuded by landslides.

These failures ranged in volume from a fraction of a cubic meter to a few hundred thousand cubic meters. Some of the larger slides traveled several hundred meters from their sources. In some cases, landslide debris completely filled canyon bottoms, or traveled as far as 200 meters onto flatter areas beyond the bases of slopes. The debris in canyon bottoms poses a secondary threat because it can be mobilized during rainstorms to form debris flows. Such flows are common, problematical, and often disastrous throughout southern California, and their potential may now be enhanced in the earthquake-affected areas.

Deeper, more coherent landslides called slumps and block slides numbered in the tens to hundreds, and occurred primarily in the Santa Susana and Santa Monica Mountains. Although these were far less numerous than the shallow slides and falls, they contributed significantly to the total volume of landslide material because they tended to be much larger. A few of these features had volumes of several million cubic meters. Most of these occurred along a single ridge between Piru and Castaic Junction where a weak clay formation is exposed in the mountains.

Landslide damage to buildings, roads, pipelines, and other structures was not as severe as it might have been in a more extensively developed area. However, landslides blocked many roads in the Santa Susana and western San Gabriel Mountains, hampering relief efforts and exacerbating the overall transportation problems caused by the earthquake. Landslides did extensive damage to roads, pipelines, and well machinery in oil fields in the Santa Susana Mountains. Dozens of homes in the central and eastern Santa Monica Mountains were moderately or severely damaged by movements of large block slides. ◆

Photo: USGS/ R. Jibson

The light-colored areas in this photograph are slopes laid bare by landslides in the Santa Susana Mountains caused by the earthquake.

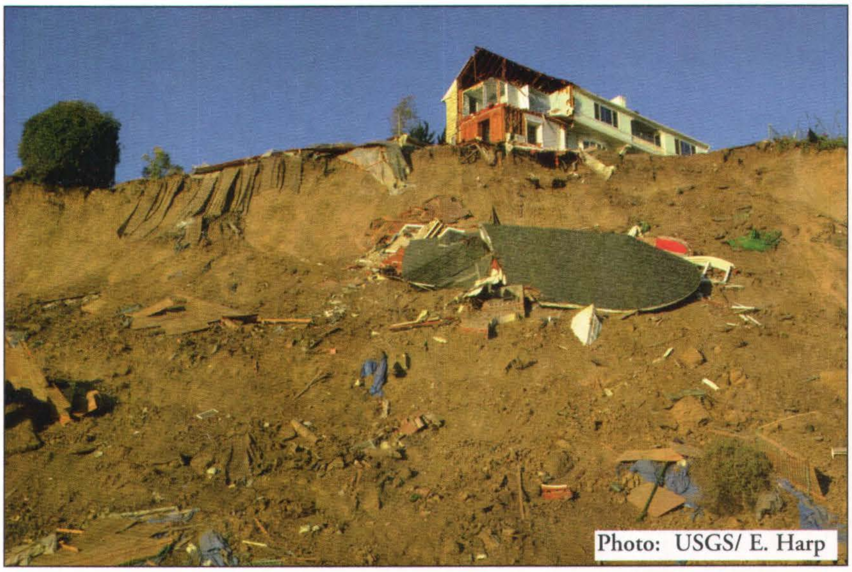


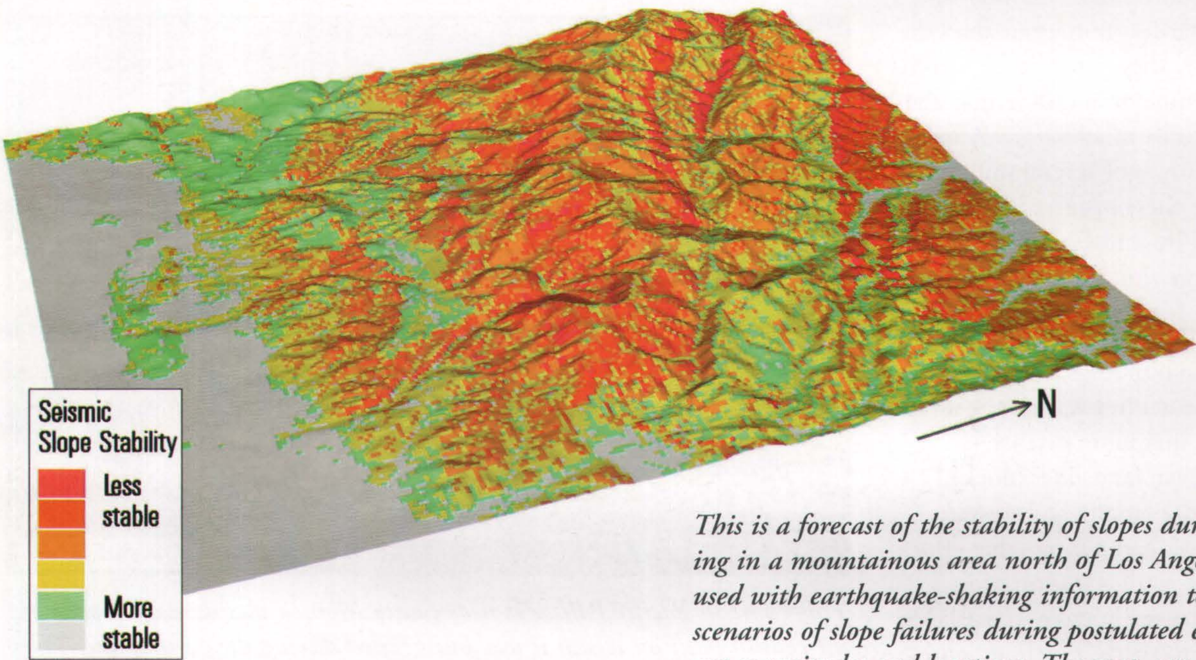
Photo: USGS/ E. Harp

This home in Pacific Palisades near Santa Monica was damaged when the coastal bluff on which it was built failed during the earthquake. The landslide caused half the house to be torn loose and cascade down the steep slope.

Landslide Susceptibility—Where Do Future Dangers Lie?

USGS scientists are using various properties of slopes and earthquake shaking to forecast the stability of slopes during future earthquakes in the region. The forecast is in the form of a susceptibility map of the Los Angeles 1:100,000 topographic map quadrangle. An example of a part of the ***susceptibility map*** shown here indicates 6 degrees of stability of slopes during earthquakes, ranging from extremely stable to unstable. Principal characteristics of the map are its great detail and its digital format. Additionally, the map was constructed in collaboration with county geologists, the California Division of Mines and Geology (CDMG), private consulting firms who are the people and entities most likely to need and use it in the future.

The susceptibility map is constructed using data for each 10-meter-square cell in the area covered by the map. These data include slope steepness and measures of the strength of geologic materials. The data are necessary inputs to a mathematical slope-stability model that yields a single numerical value for each cell. This value is called the ***critical acceleration***, which is a measure of the level of earthquake shaking that must be exceeded to cause the slope in that cell to fail. The numerical values of critical acceleration can be grouped into colors for displays like the map sample shown on this page. Scientists can test and adjust the susceptibility map using the landslide inventory data derived from the Northridge earthquake. ◆



This is a forecast of the stability of slopes during earthquake shaking in a mountainous area north of Los Angeles. This map can be used with earthquake-shaking information to produce a variety of scenarios of slope failures during postulated earthquakes of different magnitudes and locations. The map can be used for planning development in sloping areas, emergency-preparedness planning, and predicting lifeline disruptions in future earthquakes.

Lessons Learned

The Northridge earthquake provided an unprecedented amount of high-quality data useful for analyzing instabilities in earth slopes subjected to seismic shaking. The highly detailed landslide inventories and hundreds of strong-motion records of variations in earthquake shaking allowed scientists to examine landsliding in great detail. These data, combined with high-resolution topographic and geologic data, resulted in the susceptibility map—a forecasting tool of exceptional quality and flexibility.

Scientists also learned, in the case of the valley fever outbreak, that earthquakes typically provide surprises beyond the realm of efforts to forecast hazards.

Valley Fever

A major outbreak of valley fever occurred in Ventura County in the weeks following the Northridge earthquake. In just 8 weeks, more than 200 valley fever cases were diagnosed, which is 16 times the normal infection rate. The cases were heavily concentrated in the Simi Valley rather than in the San Fernando Valley where the earthquake was centered. Both the timing and location of the valley fever cases suggests that the outbreak was caused by dust generated by landslides caused by the earthquake. Canyons in the Santa Susana Mountains, northeast of the densest cluster of valley fever cases, produced many dust-generating landslides during the shaking. Prevailing winds during and after the earthquake blew from the northeast to the southwest, and carried the dust from the canyons into Simi Valley and beyond. The valley fever outbreak led to hospitalization of more than 50 people and ultimately to three fatalities.


Photo: Photographer unknown

Dust from landsliding blows out of the Santa Susana Mountains into the Simi Valley where an outbreak of valley fever occurred following the earthquake.

Damage to the Built Environment

The vast majority of losses to property and lives caused by an earthquake involve manmade structures and the people inside. It is often said, "Earthquakes don't kill people, buildings do." Because the Northridge earthquake struck directly in an urbanized environment, effects on buildings and highway structures were strikingly clear. All NEHRP agencies undertook studies to understand the extent and causes of failures of buildings and freeway structures. The USGS performed detailed analyses of instrumented buildings, studies of aftershocks recorded in heavily damaged structures, and interpretations of the large amount of data on building damage. ◆

How Instrumented Buildings Performed

The USGS studied three significant buildings that were tested by strong shaking during the Northridge earthquake. The University of Southern California (USC) Hospital building in Los Angeles, about 35 kilometers from the fault, is a base-isolated structure. The Olive View Hospital (OVH) building in Sylmar, 7.3 kilometers from the fault, is a conventionally designed building that replaced the structure that was severely damaged in the 1971 San Fernando earthquake and later razed. Both buildings contained large arrays of instruments placed to assess accelerations and displacements throughout the buildings and to compare with the shaking of the nearby ground. The study also assessed the effects of the Whittier Narrows earthquake of 1987 on the OVH building for comparisons with the Northridge event. The Holiday Inn in Van Nuys was constructed in 1966, and experienced the effects of the 1971 San Fernando and 1994 Northridge quakes. This building suffered minor damage in 1971, but sustained major structural damage in 1994. ◆

The Base-Isolated USC Hospital Building

The USC Hospital is an 8-story building with many ***isolators*** that act like shock absorbers to damp out strong ground shaking. The building contains 149 isolators that support a steel superstructure on continuous concrete spread footings. Diagonally braced perimeter frames, supported by 68 isolators, were designed to carry the lateral loads and the internal columns that carry the vertical load were supported by 81 isolators. The building, within 15 kilometers of the Newport-Inglewood fault zone, was designed for a maximum relative isolator displacement of 26 centimeters, and to meet the seismic standards of the 1988 and 1994 Uniform Building Code (UBC).

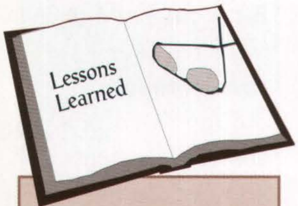
The motions recorded at the top of the isolators and at the roof were smaller than those recorded below the isolators and in the ***free field*** (a ground site away from and free of the influences of the building). These findings provide clear evidence that the isolators were effective in dissipating the vibrational energy traveling from the free field to the building. In general, the shapes of the spectra of recorded components of motions are well enveloped by the building code spectrum, except for some high frequency (>1 hertz) bands for which the code spectrum is exceeded. Accelerations at various levels of the building, and the amplitude spectra and relative displacements of the isolators confirm excellent performance throughout the building. ***Drift ratios*** (displacements within a building story at the top relative to the base) reached only 10% of allowable values explaining why there was little damage to the structure or its contents. However, the ground motions at this site were only moderately strong. USGS studies showed that displacements near the seismogenic fault of the Northridge quake would exceed the designed displacement range for the isolators. Therefore, the performance of the isolators could be a problem at the USC Hospital should shaking be stronger than that of the Northridge earthquake. ◆

Base-isolated buildings are a relatively recent addition to U.S. earthquake-resistant design strategies. In base-isolated structures, the building is insulated from strong ground motion by energy-absorbing systems between the building and its foundation. Such buildings are still uncommon because the design concept had not been tested by severe earthquakes prior to the Northridge event.

The structural responses derived from strong-motion recordings in buildings actually shaken by earthquakes can be compared to the theoretical responses that were used in designing the structures. These comparisons may verify the calculations and the stability of the design, or they may point to problems that need to be corrected in future construction. Performance of the USC Hospital building showed that design improvements are needed for the type of base-isolation system used in the building.

Prior to the Northridge earthquake, structural engineers believed that modern buildings constructed with specially designed steel frames could resist very intense ground motions with only limited structural damage. However, during the earthquake, the steel framing of more than 100 such structures experienced fractures. The fractures initiated at the welded connections between the beams and columns of the frames. These fractures were initially attributed to poor quality workmanship in the welding of the connections. However, a review of historical test data and tests performed immediately following the earthquake demonstrated that connections with standard quality workmanship were vulnerable to the fractures. Many of the damaged buildings were at sites that experienced ground motions approximating those adopted by the building code as a basis for design. Consequently, the adequacy of the building code provisions was immediately questioned, and the International Conference of Building Officials (ICBO) adopted an emergency code change in October 1994. The ICBO action prompted the creation of a joint venture among the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC), and the California Universities for Research in Earthquake Engineering (CUREE). The joint venture, simply named SAC, initiated a program to resolve the issues related to the steel-frame damage, and to publish advisories and guidelines. SAC published several interim documents during 1995 to assist engineers and building officials in design and inspection activities while reliable new building codes were being developed for steel-frame buildings. This effort was funded by the Federal Emergency Management Agency (FEMA).

The Olive View Hospital Building



The stiff design of the Olive View Hospital performed very well during the Northridge earthquake, probably saving many lives in a region of very intense shaking. Although the structure did not sustain damage, the hospital had to be evacuated because of broken water pipes and other secondary damage. These elements of the interior design need to be improved in anticipation of future earthquakes.

The OVH building was designed in 1976 to withstand increased levels of seismic forces based on the disastrous fate of its predecessor. The structural system for resisting lateral forces is a mixed design of concrete and steel shear walls. The foundation consists of spread footings and concrete slab-on-grade for the ground floor. The ground floor and second floor are typically built of concrete shear walls 25 centimeters thick that extend along several column lines. At the third level, the plan of the building changes to a cross shape, making a 4-story tower with steel shear walls surrounding the perimeter.

USGS engineers examined the building's performance by using data from both the Northridge and Whittier Narrows earthquakes for comparisons. The building was designed for two levels of performance. The first level, 0.52*g*, represented accelerations at which the building would not be badly damaged. The second level, 0.69*g*, represented accelerations at which the building would survive, perhaps with major damage but without catastrophic failure.

Data from sensors in the OVH building show that the building escaped the impact of long-period (>1 second) pulses generated by the Northridge quake. The OVH records indicated that very large peak accelerations at the ground level (0.91*g*) and the roof level (2.31*g*) were accommodated by the building without structural damage. Analyses of the data indicate that the structure was in resonance at frequencies between 2.5 and 3.3 hertz. These frequencies are also within the site-response frequencies of 2-3 hertz, calculated from examining the geological materials upon which the structure was built. The effective structural frequencies derived from the Northridge and Whittier earthquakes data are different and exhibit variations attributable to nonlinear effects. One effect is soil-structure interaction which was seen to be more pronounced during the Northridge event. The building possibly experienced rocking at 2.5 hertz in the north-south direction during that event, and there is the possibility that ***radiation damping*** (wherein the building dissipates energy into the surrounding soil) contributed to reducing that response. Damping ratios for the building were 10%-15% (north-south) and 5%-10% (east-west) for the Northridge effects, and 1%-4% (north-south) and 5%-8% (east west) for the Whittier effects. These nonlinear effects that tended to reduce the shaking of the building during large ground motions are consistent with the different damping ratios observed during the Northridge and Whittier Narrows events. There was also nonlinear behavior due to minor structural damage during the Northridge earthquake. It is also likely that the cruciform wings responded with a different frequency than that of the overall building.

The Olive View Hospital building was conceived and designed as a very strong and stiff structure, particularly in response to the disastrous performance of the original OVH building during the 1971 San Fernando earthquake. However, the resulting design placed the fundamental frequency of the building within the frequency range of the site (2-3 hertz), thereby producing conditions for resonance. This case study indicates that determining the site frequencies needs to be emphasized in developing design response spectra. Despite the site resonances, the performance of the OVH building was considered to be a great success during the Northridge event. The hospital sustained no structural damage under very strong shaking (greater than 2*g*) at the roof level. ◆

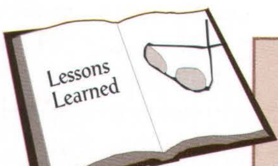
The Holiday Inn in Van Nuys

The Holiday Inn in Van Nuys is a 7-story, reinforced concrete building built in 1966. The earthquake resistance system consists of frames around the perimeter, and a foundation of concrete pilings. The building was instrumented with three accelerographs prior to the 1971 San Fernando earthquake and, thereafter, with 16 accelerometers that recorded the Northridge quake. The building is located approximately the same distance from the seismogenic faults of both earthquakes (see p. 18). During the San Fernando earthquake, the building suffered minor damage that was mostly nonstructural. During the Northridge event, however, the building suffered extensive structural damage. USGS scientists used the records from both earthquakes to determine reasons for the difference in the amount of damage.

The peak ground-level accelerations for the San Fernando earthquake were 0.25*g*, 0.14*g*, and 0.17*g* in north-south (transverse), east-west (longitudinal), and vertical directions, respectively. The corresponding values for the Northridge quake were 0.42*g*, 0.44*g*, and 0.28*g*. The peak roof displacements relative to the ground for the San Fernando quake were 15 centimeters in the north-south direction and 8 centimeters in the east-west direction. For the Northridge quake, the peak north-south displacements were 17 centimeters for the east end of the building, and 23 centimeters for the west end. The peak east-west displacement of the roof with respect to the ground was 23 centimeters. The large difference between the east- and west-end displacements indicated a significant amount of torsion in the building. Using data from roof sensors, USGS engineers determined that the building was rotating with respect to a center near its east end during the Northridge event. The building lacked sufficient instruments during the San Fernando event to record comparative torsional modes.

USGS engineers analyzed response spectra for the building for the San Fernando and Northridge earthquakes. The analysis showed that the building responded with much larger amplitudes to the Northridge quake than to the San Fernando quake, and that the response spectra for the Northridge event exceeded the Uniform Building Code (UBC) response spectra. Ground-to-roof transfer functions showed that the north-south vibrations of the building were coupled with torsion in both earthquakes. The dominant frequency of this mode was near 0.7 hertz. The east-west vibrations had dominant frequencies of 0.9 hertz during the San Fernando earthquake and 0.5 hertz during the Northridge event. The Northridge frequencies are those after failure of the fourth-floor columns. ◆

Ground-motion data to support the investigations described on pages 48-53 were obtained in part from the California Division of Mines and Geology (CDMG) strong motion instrumentation program (see p. 24).

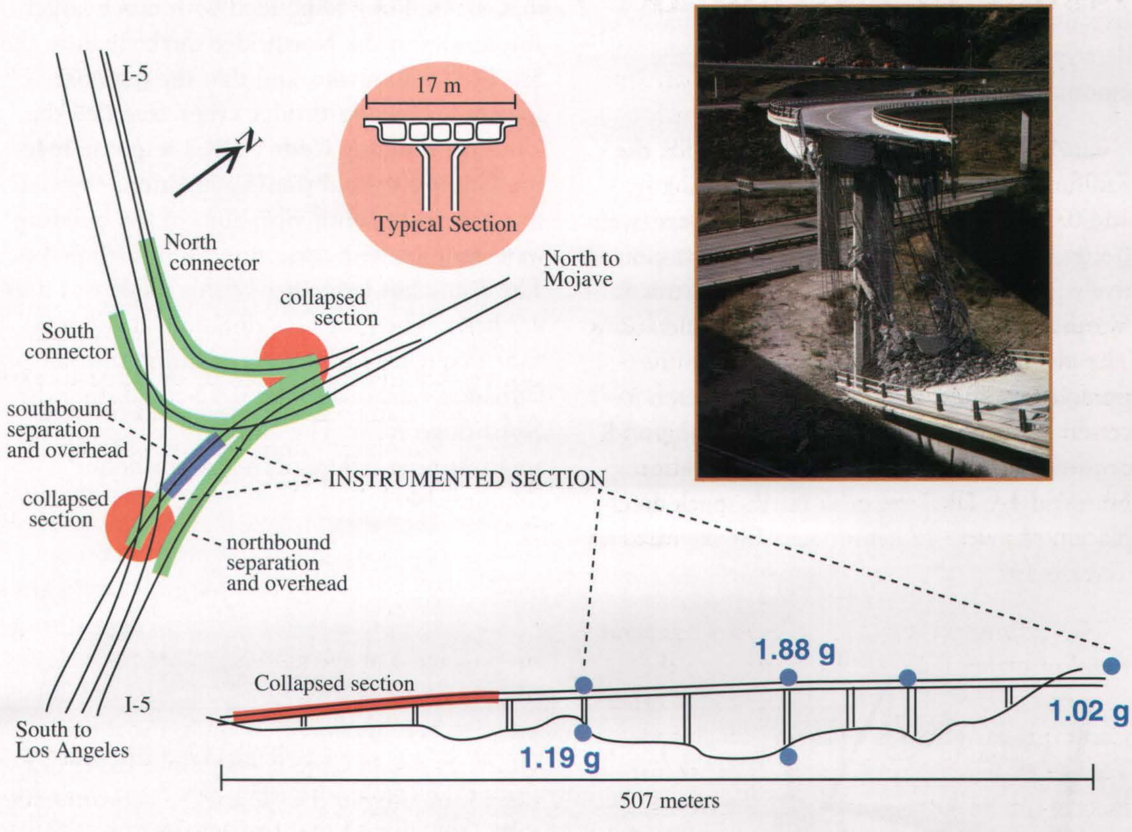


The Holiday Inn in Van Nuys was severely damaged during the Northridge earthquake, after suffering only minor damage in the 1971 San Fernando earthquake. Reasons for the different responses were essentially due to the stronger shaking at this site during the Northridge quake. The building was subject to significant torsion during the Northridge event, and the spectral response of the building exceeded that of both the San Fernando earthquake and the Uniform Building Code.

The Collapse of the Interstate-5/ State Highway-14 Interchange

The collapsed I-5/SH-14 interchange (see cover) was one of the most spectacular and costliest damage sites resulting from the earthquake. To determine what happened at the site, USGS scientists deployed instruments on the standing sections of the interchange bridges and on the surrounding ground at the bases of pier supports. The instruments were used to obtain aftershock records for (1) determining the dominant vibrational modes in which the bridges responded to shaking, and (2) estimating the main-shock motions responsible for the collapse.

Using accelerations and velocities from the four largest aftershocks, USGS engineers calculated ground-to-deck ***transfer functions.*** These functions defined the transfer of vibration from the ground to the bridge deck in the horizontal and vertical directions, and longitudinally along the bridge spans. Different methods for calculating the functions gave consistent estimates of dominant frequencies of the deck—0.4, 0.7, and 3.2 hertz in the horizontal, longitudinal, and vertical directions, respectively.



USGS engineers placed instruments throughout a section of the freeway bridge adjacent to the section that collapsed during the earthquake. Using aftershock recordings and data from nearby stations that recorded the main shock, they were able to relate the collapse to accelerations that greatly exceeded those for which the bridge was designed. Accelerations calculated for the base of the bridge (1.19g and 1.02g) translated into an acceleration of 1.88g on the deck. The 1.88g value represents conditions of the failed structure, and not those of the original continuous structure.

Because there were no strong-motion instruments at the bridge to record the shaking, engineers used innovative methods to estimate the main-shock motions that caused the collapse. One method used relations between the main shock and aftershocks determined for three nearby strong-motion stations. Aftershock motions from the bridge structures were then scaled by these relations, giving consistent estimates of ground motions at the bridge from the main shock. The response spectra showed very large amplitudes, particularly for the longitudinal direction, for periods less than 1 second. The peak spectral amplitudes calculated for the main shock were three to four times the design spectra in this period range.

The methods used here were an attempt to demonstrate using aftershock recordings to estimate main-shock motions. Much more detailed analysis of connectors, local geology, and other factors would be needed to determine, for example, why the collapse occurred on the lower rather than the higher sections of the structure. ◆

Larger Than Expected Ground Motions and Issues of Earthquake Engineering

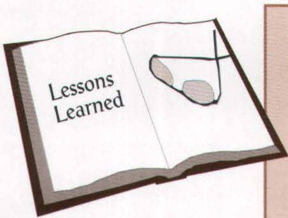
USGS scientists studied more than 250 ground-motion records from major networks operated by the USGS, the California Division of Mines and Geology (CDMG), and the University of Southern California (USC), and smaller networks such as one operated by the Los Angeles Department of Water and Power. In general, peak accelerations exceeded those predicted by attenuation relations for California. At several locations, horizontal peaks were close to or exceeded 1*g*, and at one station, the peak vertical acceleration exceeded 1*g*. The largest horizontal peak acceleration of a free-field site was 1.78*g* recorded in Tarzana (see p. 29).

The ground-motion data indicated a general trend of higher peak accelerations from the Northridge earthquake than for those of other California earthquakes of similar magnitude. This trend may be attributable to the thrust mechanism and the effects of directivity (see p. 12). Ground motions both near and far from the epicenter contained consistent high-energy pulses of relatively long duration, a cause for concern about the vulnerability of mid-rise to highrise steel structures designed for lesser motions. Additionally, there were significant site effects contributing to the overall picture of unexpected ground motions.

The strong-motion records show that long-duration pulses contributed to the large accelerations that damaged numerous mid-rise and highrise buildings. Long-duration pulses produced large ground velocities and displacements. Consequently, significant percentages of wave energy were transmitted to structures within the duration of the pulses, which commonly were within the 1-5 second period common to most of the buildings. Ground-velocity records analyzed for stations 10, 16, and 20 kilometers from the epicenter indicate that buildings need higher strength and larger ductility (flexibility of a structure) to accommodate the velocities without damage. ◆

The Myth of Unusual Vertical Motions

Following the Northridge earthquake, there were statements by engineering and other professionals to the effect that much of the structural damage was caused by unusual vertical motions. This is not true. The ratio of horizontal to vertical shaking was similar to that of past earthquakes. One factor that contributed to the misconception was that vertical shaking is always stronger in the epicentral region. For the Northridge event, there were many structures in the epicentral region that were subjected to strong (but not unusual) vertical motions.



The shapes of the response spectra of motions at many sites exceeded the Uniform Building Code (UBC) spectra beyond T>0.5 seconds for "soil-like" sites (called S2 in the UBC). Many motion spectra from "rock-like" (S1) sites exceed the UBC spectra in the short-period range. The averages of the normalized spectra are enveloped reasonably well by the UBC design-response spectra for either S1 or S2 sites. The standard deviation above the average is significant, however, for S1 sites. Therefore, a spectral peak of 3.0 (compared to the current value of 2.5) for the 0.1-0.5 second range of building response should be used for S1 sites, and similar increases are proposed for S2 sites. Sites that experienced unusually high accelerations, such as in Newhall and Tarzana, bear further consideration as to special designs to accommodate such accelerations.

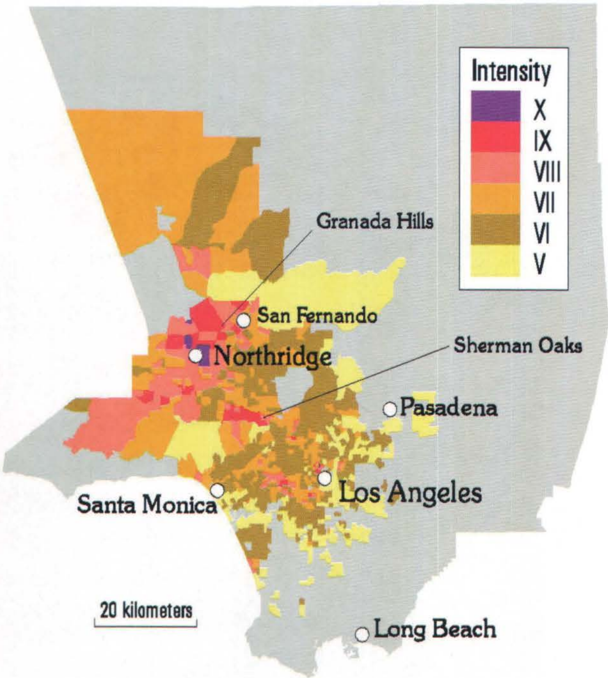
Predicting Building Damage and Loss

The California Office of Emergency Services (OES) compiled a detailed data set on building damage throughout southern California (see p. 8). The data set identifies the types, geographic distribution, and damage, if any, of buildings that were inspected and "tagged" throughout Los Angeles County. The data set is separated into 12 building categories differentiated by date and type of construction. USGS scientists used the data set to map shaking intensity in the county and to develop a method for predicting future damage and loss from earthquakes.

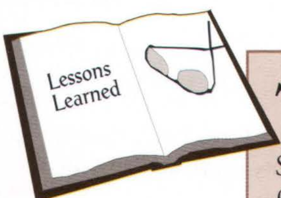
Scientists selected seven building categories to give the most complete areal coverage for the analysis. Five of these categories were wood-frame residential structures comprising pre- and post-1940 single-family, pre- and post-1940 2- to 4-family, and post-1940 multifamily dwellings. The other two categories were 1940-76 and post-1976 masonry structures. The data were aggregated by 1990 Census tracts in order to give the highest resolution to the coverage. In the San Fernando Valley, Census tracts cover about 1.5 square kilometers on the average, and in downtown Los Angeles, they cover about 1 square kilometer. The most densely populated Census tracts contain more than 2,000 residential structures.

USGS scientists developed a mathematical relation that estimates shaking intensity by comparing "red-tagged" (no occupancy allowed) buildings in the post-1940, single-family-dwelling category to exposed buildings in a Census tract. The estimator uses a ***damage matrix***, derived from data from the 1989 Loma Prieta earthquake in northern California, that predicts the ratio of "red-tagged" to exposed buildings for Modified Mercalli Intensities (MMI) in the range V to X (see p. 9). The relation then is modified using damage matrices for other building categories and for the "yellow-tagged" (limited entry allowed) and "green-tagged" (no restrictions on entry) data. The resulting equation yields a ***tagging intensity*** that reflects the utility of the various tags for estimating different shaking intensity levels. For example, the "red tags" predict the higher MMI intensities (IX and X+) much more reliably than the lower intensities.

The analysis showed that the post-1940 single-family dwellings constitute both the largest building category, and the strongest in terms of resistance to damage from earthquake shaking. Post-1940 multifamily dwellings proved to be more susceptible to shaking damages than the categories of masonry buildings or pre-1940 single-family and 2- to 4-family wood-frame dwellings. ◆



A new shaking-intensity estimator, called the tagging intensity, is based on building-inspection data. Tagging intensity, mapped by Census tracts in Los Angeles County, shows damage clusters in the San Fernando Valley in Northridge, Granada Hills, and Sherman Oaks. In the Los Angeles basin, there are damage clusters in and to the west-southwest of downtown Los Angeles. In general, the shaking intensity calculated by the estimator exhibits greater detail and variability than the MMI intensities delineated for the region.



The dense areal coverage of tagging data for Los Angeles County yielded the most detailed estimates of damage and shaking intensity ever obtained for an earthquake in the United States. Crosscorrelating damage in seven building categories revealed that the post-1940 multifamily dwellings were more susceptible to damage than the two masonry-structure categories or the two pre-1940 wood-frame dwelling categories. These results will strongly condition predictions for building damages and losses from future earthquakes in California.

Making Choices About Earthquake-Hazards Mitigations

Current Federal and State legislations contain a myriad of economic incentives for mitigating specific hazards to buildings, such as bolting a structure to its foundation. The Robert T. Stafford Disaster Relief and Emergency Assistance Act (Public Law 93-288), the Alquist-Priolo Special Study Zones Act (California Public Resources Code, 1974), and the California Seismic Hazards Mapping Act of 1990 all contain provisions for market incentives and administrative actions to promote public safety and property-loss reduction. As a result, a variety of market incentives have been implemented. The rules and market incentives associated with these acts require site-specific engineering study and review in recognized hazardous areas. However, many vulnerable locations are not well known and are distributed unequally in hazards-prone regions. For example, the Northridge earthquake occurred on a previously unknown fault, albeit in a region generally known for its earthquake hazards. This mismatch of information creates a market uncertainty that could affect a hazards-mitigation strategy. USGS work on this issue investigated risk assessment methods based on scientific data that can be applied to earthquake hazards. These methods are intended to evaluate the cost-effectiveness of earthquake-hazards mitigation.

One of the real successes of earthquake preparedness in southern California is the Los Angeles City program to retrofit unreinforced masonry buildings (URM's). Since 1982 several thousand of these structures have been repaired, some in areas that were strongly shaken by the Northridge earthquake. Although it is difficult to quantify the benefits of retrofitting, the savings in lives and property for the Northridge earthquake alone has more than justified this ordinance.

The risk-assessment model can be applied to the problem of earthquake earthquake-hazards mitigation choices using the following steps:

(1) Establish a ***decision framework*** by defining a benefit-cost analysis for earthquake-hazards mitigation choices and measures;

(2) Develop a ***physical model*** that incorporates strong ground motions and site characteristics;

(3) Establish a conceptual model for ***safety incentives*** that incorporates the rules for making alternative safety decisions;

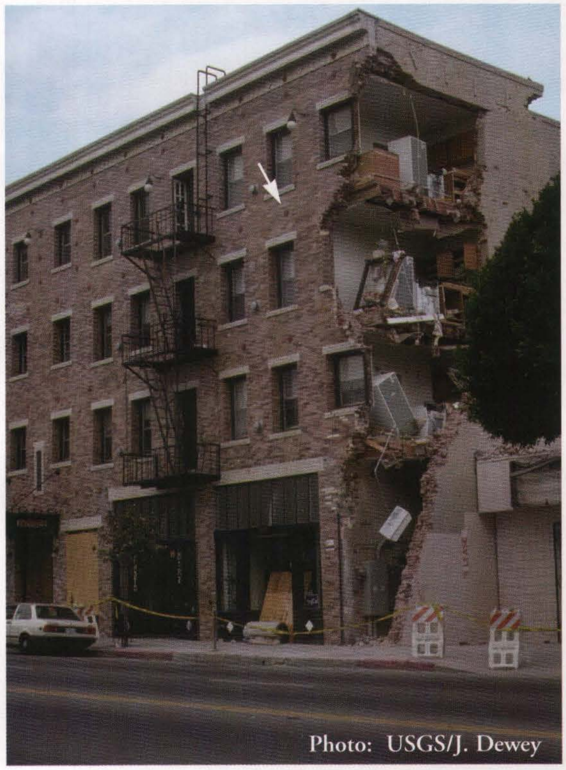


Photo: USGS/J. Dewey

This masonry building near downtown Los Angeles was badly damaged during the Northridge earthquake. Prior retrofitting, evidenced by the lines of bolts (reddish, circular features indicated by the arrow), probably prevented more extensive collapse.

(4) Develop a ***descriptive model*** that integrates the spatial and temporal structure for earth-sciences and economic information;

(5) Formalize step (3) with empirical data to produce a ***prescriptive model*** that represents what should be done to maximize the benefits of mitigation; and

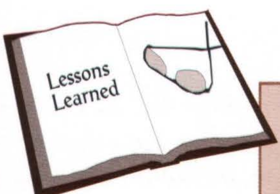
(6) Apply a ***probabilistic model*** to identify the optimal strategy from the feasible mitigation choices identified in (5).

A good example of applying economic modeling is evaluating the choices consumers make in preparing for earthquakes. People can purchase earthquake insurance, carry out personal or community mitigation efforts, do nothing, or combine several of these activities.

Consumers in an earthquake-prone region are faced with making choices about personal safety that involve such factors as the probabilities of earthquakes, potential damages, and appropriate mitigation activities. In addition, consumers need public information about these factors. The economic model combines the probability of a hazard, the property value at risk, and the cost of various mitigation activities.

In general, the decisions of an educated consumer are based on avoiding losses. Thus, if a consumer is classified as benefiting from a strategy that reduces losses, there is a net gain in consumer welfare, and the consumer has an incentive to purchase mitigation measures. Under these conditions, it is clear that public education and information can result in large economic savings within a hazardous region. In an ideal world, consumers would be informed by public agencies of the time, location, magnitude, and local site effects of a future earthquake, and would make rational decisions. However, scientific data about the recurrence of damaging earthquakes and the geographic vulnerability of specific sites cannot be precisely determined. We have seen that it is very difficult to predict even the location of damaging earthquakes. Therefore, occurrences of seismic hazards typically are stated in terms of spatial and temporal probabilities that can be used in decision making.

Earthquake insurance and building codes are accepted measures to reduce damages. Earthquake insurance policies have seemingly large deductibles and substantial annual premiums. For example, a representative policy will include a deductible of 10% of insured value and an annual premium of $2 per $1000 of coverage. Earthquake-related building codes generally are minimum provisions that are necessary for ensuring structural integrity during shaking. However, such codes commonly do not address the collateral effects of earthquakes (such as landsliding) that temporarily exacerbate the potential for damage. Mitigation for a specific hazard may involve major construction activity, such as foundation alteration, retrofitting internal structural support, or other expensive or extraordinary measures. Thus, for each mitigation choice there is a planned beneficial effect and a known cost to achieve the specified level of protection. ◆



Analyses of the economic impacts of the Northridge earthquake demonstrated that pre-event mitigation decisions helped avoid significant loss of life and additional property damage. However, there will be more damaging earthquakes in the future in the region. Economic modeling provides a means for consumers to evaluate different mitigation choices and incentives. Using a refined model with more complete earth-science information, consumers can apply economically sound decisions about risk-based regulations or insurance programs containing incentives for mitigation.

Earthquake-Hazards Assessment—

Seismic-Hazards Maps for the Los Angeles Region

Seismic-hazards maps are among the principal connections between research on earthquakes and hazards mitigation. Such maps, produced for the United States since 1976 by the USGS, are the basis for the seismic parts of model building codes such as the Uniform Building Code (UBC). The maps also have wide-ranging applications in a variety of structural-design requirements such as those governing highway bridge design. Insurance companies use the maps to help set rates for individual properties in various areas of the United States. FEMA also uses the maps to help determine allocation of Federal disaster assistance funds to communities damaged during earthquakes.

With continuing research, and using the information gained from each new earthquake, seismic-hazards maps are frequently updated. Following the Northridge earthquake, new maps were constructed for the Los Angeles region. These maps are currently (1996) in review and will be revised and produced cooperatively with the California Division of Mines and Geology (CDMG). This effort is supported by FEMA disaster-mitigation funds.

The maps incorporate both the recurrence rate and expected magnitudes of large earthquakes along each fault capable of generating earthquakes. The maps also account for hazards from future earthquake events that could occur, for example, on buried or unmapped faults. The maps show ground motions that have a specified annual probability of being exceeded—important information used for engineering buildings to withstand the ground motions expected over their design lifetimes.

The preliminary map for the Los Angeles region illustrates that seismic hazards are manifestations of (1) strike-slip motion along the San Andreas, San Jacinto, and other faults; and (2) broad, north-south compression caused by the "Big Bend" in the San Andreas fault east and north of the Los Angeles area. This map shows high seismic hazards throughout most of southern California where probabilistic ground motions during a 50-year period generally exceed 30%*g*. Many heavily developed areas near Los Angeles have mapped ground motions that exceed 40%*g*, primarily due to the presence of the Newport-Inglewood and Palos Verdes faults. There are also substantial hazards associated with the confluence of the Sierra Madre and Raymond faults, which accommodate north-south compression (see p.18).

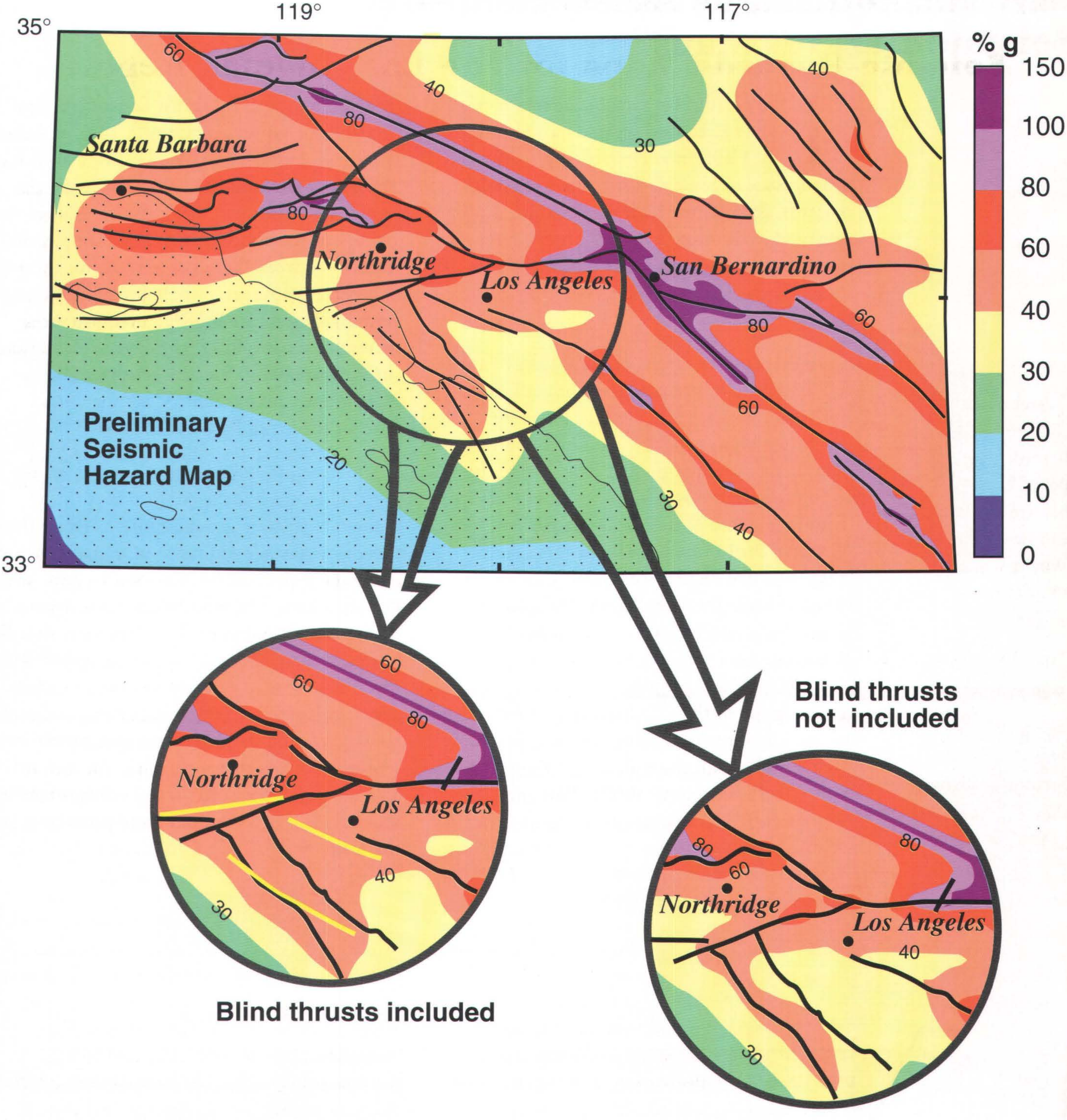
Higher values of hazards (greater than 60%*g*) occur along the San Andreas, San Jacinto, and Elsinore faults. These strike-slip faults have relatively high slip rates and recurrence times as short as 150 years for certain segments. High hazards occur where faults intersect or are adjacent to each other, because these locations are more likely to experience large ground motions from both of the adjacent faults. The area of highest seismic hazards (with a 10% probability of exceeding 100%*g* in a 50-year period) is near San Bernardino, which is adjacent to both the San Andreas and San Jacinto faults.

A prominent zone of higher hazards extends from south of Santa Barbara to the northern part of the San Fernando Valley and the bordering mountains. This is caused by a group of thrust faults with relatively high slip rates, exemplified by the Oak Ridge and San Cayetano faults. The new hazards map emphasizes the importance of blind thrust faults (similar to the fault that produced the Northridge earthquake) to the seismic hazards of the Los Angeles region. ◆

Preliminary versions of seismic-hazards maps prepared by the USGS for the United States can be seen on the World Wide Web at the following address:

http://geohazards.cr.usgs.gov

As newer maps and related information become available, they will be placed at this WWW site.



This preliminary seismic-hazards map is based on both historical seismicity and recurrence times of fault movements derived from geologic slip rates. The circles show how a section of the map would appear with and without the effects of blind thrusts (yellow lines). Given the uncertain seismic potential of the blind thrusts, scientists modified the preliminary map to account for the uncertainties. This map depicts peak horizontal ground accelerations that have a 10% probability of being exceeded in 50 years.

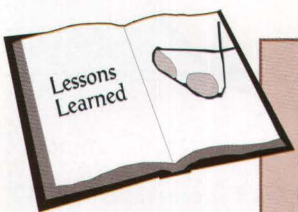
How the Northridge Earthquake Affects Seismic-Hazards Maps

The Northridge earthquake had two primary effects on seismic-hazards maps for California. First, it emphasized the importance of blind thrust faults to seismic hazards. Second, the high accelerations during the quake reinforced previous observations that earthquakes on thrust faults produce higher ground accelerations than those on strike-slip faults.

To evaluate the effects of blind thrust faults, USGS scientists produced two hazards maps for situations with and without four recently identified blind thrust faults. The blind thrusts considered were the Elysian Park thrust, the Compton-Alamitos thrust, the Santa Monica Mountains thrust, and the Santa Barbara Channel thrust (see p. 18). For these faults, they used two recurrence models that are weighted equally in the hazards calculation: (1) a characteristic fault-rupture model where the entire fault ruptures at some average recurrence rate, and (2) another model where there is a range of earthquake magnitudes occurring on each fault, with M = 6.5 events being more frequent than larger events that rupture the entire fault. Each recurrence model was given a weight of 0.5 because of uncertainties about the seismic potential of the thrust faults, and the inferred dips of the thrusts were included when calculating site-source distances.

Including the blind thrust faults raises the probabilistic ground motions (a 10% probability of being exceeded in 50 years) by as much as 15%*g* for areas near the faults. There are also significant changes in the 40%*g* contour in the vicinity of the blind thrusts. For example, differences between the maps are seen for the area of central Los Angeles where probabilistic accelerations increase from 38%*g* to 45%*g* with inclusion of the blind thrust faults. There were similar increases in the area southwest of Northridge, and for Santa Cruz Island and parts of the Santa Barbara Channel.

The large ground motions recorded for the Northridge earthquake confirm that thrust faults can generate ground motions larger than those of strike-slip faults for earthquakes of similar magnitudes and site-source distances. USGS scientists have found that thrust-fault earthquakes produce peak accelerations near the source that are about 20%*g*-30%*g* higher than those of strike-slip earthquakes. These differences are directly reflected in the maps of probabilistic ground motions. As new ground-motion relations that include the Northridge data are developed, the effects of thrust faulting probably will become even more prominent on the maps. ◆



Blind thrust faults, such as the one that produced the Northridge earthquake, increase the seismic hazards for the Los Angeles region. The very presence of these additional faults adds to the hazards, and thrust faults also tend to produce stronger ground motions than strike-slip faults.

Past Earthquakes and Scenarios for the Future

Continuing efforts to reduce the threats of earthquakes in an effective and practical way requires knowledge of the levels of hazards in different areas. Future earthquakes are most likely to originate where strain surrounding a fault has built up and has not yet been released in earthquakes. In southern California, for example, scientists estimate that the probability of a magnitude 7 or greater earthquake by the year 2024 is as high as 80%-90%. How the threat from earthquake ground shaking varies across southern California is shown on hazards maps like those described in the previous section, and elsewhere in the report (see p. 25). These hazards maps are derived from decades of work by scientists in government, universities, and private industry. Such work continually refines hazards estimates, incrementally correcting and updating the hazards overview as new information and techniques become available. The following sections offer some insights into the fundamental work that contributes to hazards assessments through reviewing the effects of past earthquakes, modeling what earthquakes might do in the future, and comparing the effects of different earthquakes on the same or similar facilities. ◆

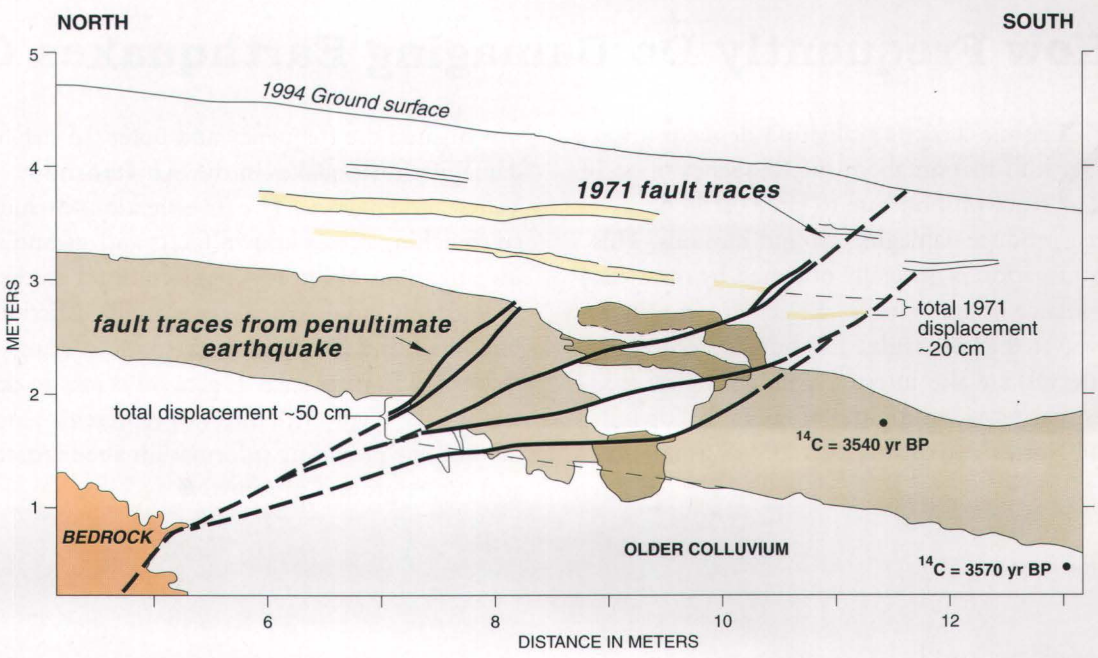
How Frequently Do Damaging Earthquakes Occur?

Seismic-hazards evaluation depends upon information about the frequency of occurrence of moderate to large earthquakes that produce damaging ground motions. This information is generally obtained by observing evidence of past earthquake activity in trenches excavated across faults. Earthquake recurrence intervals are also inferred from geological studies that provide slip rates of faults. Following the Northridge earthquake, USGS geologists investigated the frequency and potential size of damaging earthquakes in the San Fernando Valley and environs. The investigations included trenching across known faults and subsurface investigations of linear zones of ground cracks in Potrero Canyon, the Granada Hills-Mission Hills area, and Northridge (see p. 33). Using secondary features such as ground cracks to date earthquake recurrence intervals represents a new method for providing information about past and future ground motions. ◆

The main goal of trenching studies is to examine closely the disrupted geological deposits in fault zones by exposing cross sections of the zones. Careful mapping of the deposits and the fault traces and other features within them can identify the nature of ruptures from past earthquakes. Organic materials in the deposits, such as charcoal or peat, can be used to date disruptions and produce a history of earthquakes that affected the site. The study of earthquake-related features preserved in the geologic record is called paleoseismology.

Earthquake History Along the Sierra Madre Fault—Revisiting the 1971 San Fernando Earthquake

After the 1971 San Fernando earthquake, USGS geologists excavated several trenches across the rupture zone and estimated that a prior event might have occurred about 200 years ago. Following the Northridge earthquake, scientists excavated three new trenches in the area of the 1971 faulting and found new evidence suggesting the prior event was much older than 200 years. The new trench data show a clear 20 centimeters of vertical displacement caused by the 1971 event, plus older deposits with a much larger vertical displacement of about 50 centimeters. Distinctive sands and gravels that can be matched across the fault provide evidence for the two most recent earthquakes that occurred prior to 1971. Charcoal samples from the deposits and the degree of development of buried soils show that the penultimate event is older than 400 years and could be as old as 3,500-4,000 years. The timing for the other event prior to 1971 is currently (1996) being investigated. The evidence compiled to date suggests that only two earthquakes have occurred on this fault segment during the past 3,500-4,000 years, one of them in 1971, indicating a much longer recurrence interval than previously believed. ◆



The geological section across the Sierra Madre fault shows features from the 1971 San Fernando earthquake, and the penultimate earthquake that occurred as long as 4,000 years ago. The fault trace of the penultimate earthquake fractured materials (beige, stippled pattern) that were radiocarbon dated at 3,540 years before the present (BP). This fault trace also fractured the underlying deposit that was dated at 3,570 years BP. Since the penultimate earthquake, about 1.5 meters of materials accumulated atop the fractured surface. The 1971 earthquake then fractured both the older deposits and the materials that accumulated above them over the past 3-4 millennia. Geologists also measured displacements at this site of about 50 centimeters for the ancient earthquake and about 20 centimeters for the San Fernando event.

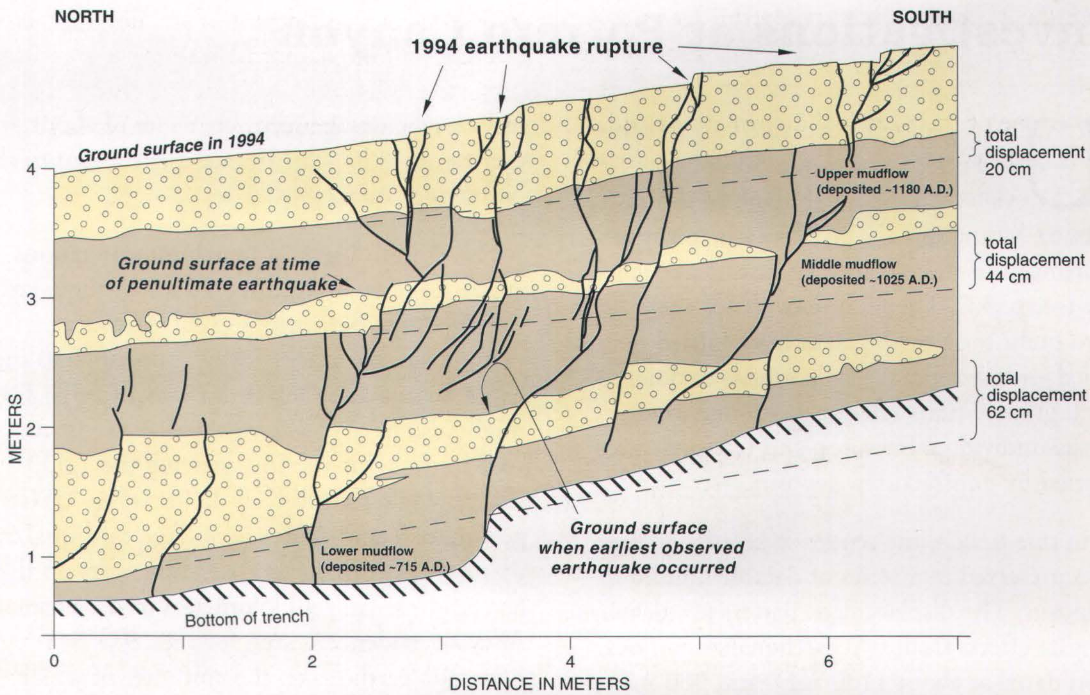
Investigations at Potrero Canyon

USGS geologists excavated 16 trenches in Potrero Canyon, a 5-kilometer-long valley on the north flank of the Santa Susana Mountains about 22 kilometers north-northwest of the Northridge earthquake epicenter (see p. 33). They found evidence there for two prehistoric earthquakes from buried fissures filled with sediment, displacement of older stratigraphic units relative to younger ones across individual fractures, and fracture traces buried by nonfractured deposits.

In one trench, the sequence of earthquakes was preserved in a series of datable mudflow deposits. The displacement patterns indicate similar effects from two earthquakes, radiocarbon dated at about 1100 A.D. and 900 A.D., and from the 1994 Northridge earthquake. As indicated on p. 41, the Potrero Canyon ground cracks appear to be caused by ground deformation related to shaking rather than primary surface faulting. Therefore, geologists conclude that there were two other earthquakes comparable to the 1994 Northridge event that produced strong ground shaking at Potrero Canyon within the past 1,300 years. These interpretations indicate an average recurrence rate of about one event every 650 years from the first event to the Northridge quake.

The Potrero Canyon trench interpretations appear to indicate recurrences for earthquakes similar to the Northridge event. However, earthquakes on other nearby faults, such as the Santa Susana and Oak Ridge faults (see p. 23), might also have produced the displacements seen in the trenches. In reviewing the 1,300-year geologic record from the trenches, USGS geologists see no evidence of large earthquakes that have occurred every 100-200 years on the San Andreas fault 40 kilometers to the north. Also, no evidence is seen for the 1971 San Fernando earthquake, the epicenter of which was located 25 kilometers southeast of Potrero Canyon. Therefore, it seems unlikely that events on the most active nearby surface faults produced permanent ground deformation at Potrero Canyon. The most reasonable interpretation of the data is that the prehistoric earthquake evidence observed in Potrero Canyon is the result of events on buried thrust faults. ◆

Identifying and trenching secondary ground-deformation features potentially provides information on earthquake recurrence intervals. This new approach, in conjunction with additional studies on other surface faults, may be widely applicable in the Los Angeles basin as a basis for estimating the recurrence of damaging ground motion from earthquakes on blind thrust faults.

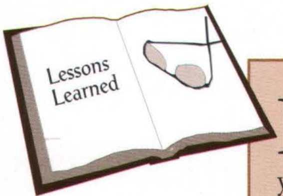


This geological section from a trench in Potrero Canyon shows relations among ground cracks from different earthquakes, offsets of geological units, and the corresponding dates that are used for recurrence estimates. The section contains evidence for ground fractures produced by three earthquakes during the past 1,300 years. The uppermost deposit was displaced about 20 centimeters during the Northridge earthquake, the top of the middle mudflow deposit was displaced about 44 centimeters in two earthquakes, and the top of the lower mudflow deposit was displaced 62 centimeters in three earthquakes. Thus, the three earthquakes produced remarkably similar effects, both in the types of features exposed in the trench and in the net displacement for each event. The fractures are thought to be the result of strong ground shaking, and do not indicate the presence of a seismogenic fault *(see p. 41).*

Investigations in Granada Hills-Mission Hills and Northridge

A zone of ground cracks in the Granada Hills-Mission Hills area (see p. 33) showed movements in the centimeter to decimeter range. USGS geologists investigated these features by excavating three trenches across prominent areas of tension cracks in the western end of the zone. These cracks appear to be a response to shaking rather than to tectonic faulting. Geological stratigraphy was similar in all three trenches, consisting of debris-flow and stream-channel deposits. None of the trench exposures showed any clear evidence of disruption from earthquakes prior to the 1994 event. Age data from the deposits suggest that in the 600 years prior to 1994, there were no earthquakes large enough to produce ground motions in this zone comparable to the motions produced by the Northridge earthquake. This interpretation is consistent with recurrence data from Potrero Canyon.

In the Malden St. area of Northridge (see p. 33), ground failure occurred in a zone about 500 meters long. Scientists excavated a trench across one of the principal deformations and found no evidence of disruptions due to earthquakes predating the Northridge event. Age data are not yet available for this site, but material properties and degree of soil development in the deposits are comparable to those seen in the Granada Hills-Mission Hills trenches. This evidence suggests that prior earthquakes large enough to produce deformations at this site have not occurred in the past several hundred years. ◆



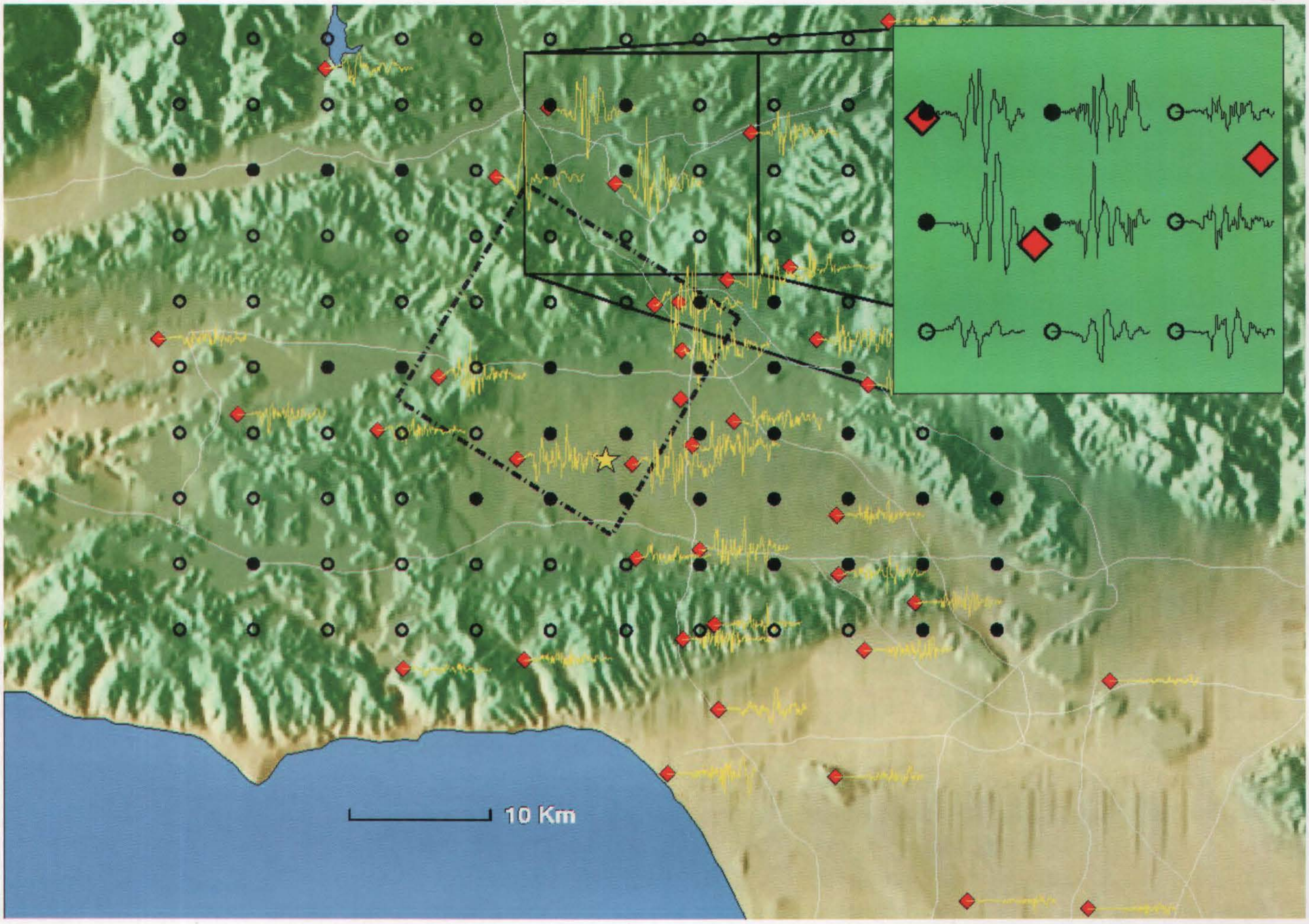
Impacts similar to those produced by the Northridge event have occurred at Potrero Canyon at two earlier times in the past 1,300 years, implying an average recurrence interval of 650 years for Northridge-type events. These impacts were most likely produced by blind thrust faulting from the nearby network of faults related to the Northridge event. The part of the Sierra Madre fault that broke in the 1971 San Fernando earthquake has had only two similar earthquakes in the past 3,500-4,000 years. The past earthquakes were most likely similar in magnitude to the more recent 1971 and 1994 events, suggesting that M = 6.5-7.0 events are perhaps characteristic of the thrust-fault structures. There is no clear evidence that larger earthquakes have occurred on these fault structures in the past few thousand years.

Predicting Ground Motions in Future Earthquakes

Once scientists have estimates about earthquake locations and recurrence, they can develop methods for estimating the levels of shaking the earthquakes will produce. This information is important for engineering design of individual buildings and for site-specific characteristics of ground motions. Following the Northridge earthquake, USGS scientists estimated ground motions (where none had been recorded) throughout a broad region surrounding the Northridge fault-rupture zone. The purpose of this work was to provide realistic, broadband ground motions that represented the range and variability of ground motions from the earthquake. This method can be used to predict ground motions for future earthquakes in the region.

Scientists first determined a fault-rupture model for the earthquake that was consistent with geodetic, leveling, strong-motion, and teleseismic data (see p. 13). Next, they superimposed a grid of target sites surrounding the fault-rupture zone. In this case, they selected a grid of 144 sites over an area of approximately 3,600 square kilometers, with a spacing of about 5 kilometers between sites. Long-period (>1 second) ground motions were computed for each grid site. High-frequency (periods <1 second) ground motions were then chosen from the observed Northridge earthquake recordings to best approximate the correct directivity, site conditions, and epicentral distance for each of the grid sites. Finally, mathematical filters were used to remove the short periods from the computed ground motions, and to remove the long periods from the observed recordings. The two filtered records were summed to produce a final ground-motion simulation for each grid site.

The final product consists of 144 three-component, broadband ground-motion time histories that can be used as input into engineering design and hazards assessment. This product allows for analyzing the damage potential of ground motions over the entire region covered by the grid, rather than relying on the observed recordings alone. The product can be used to simulate the effects of postulated earthquakes on sites throughout the area covered by the grid. Each site on the grid would show synthetic responses to that earthquake, such as ground accelerations, velocities, displacements, durations of shaking, or a range of spectral amplitudes. An investigator could then interpolate between grid points to estimate, for example, alternative engineering-design characteristics of a site. As one example, USGS scientists used the grid to produce a map of peak ground velocities throughout the region of the Northridge earthquake. The results of this analysis are shown on page 13 in their relation to the Northridge earthquake fault-rupture model. ◆



The distribution of strong-motion stations (open diamonds) illustrates the relatively sparse coverage of the region affected by the Northridge earthquake. To extrapolate information throughout the region, USGS scientists developed a method for producing synthetic ground motions for each of 144 points on a regional grid (inset). The grid allows several kinds of information for recorded and postulated earthquakes to be extrapolated throughout the region.

Inset: Using synthetic waveforms, USGS scientists computed ground velocities at these nine grid points. Compare these with the observed recordings at nearby stations.

The Los Angeles Dam Story

In 1971, the near failure of the Lower San Fernando Dam forced 80,000 people to evacuate their residences. In 1994, the replacement dam survived an almost identical earthquake with little damage. Underlying this progress in designing critical structures are years of research on the powerful shaking during large earthquakes.

Moments after the San Fernando earthquake, only a thin dirt wall stood between 80,000 people in the San Fernando Valley and 15 million tons of water poised behind a heavily damaged dam. The 47-meter-high dam was perilously close to failure, and at any moment a strong aftershock could have triggered a disaster. Residents in a 30-square-kilometer area were forced to evacuate while the water level behind the earthen dam was lowered, a process that took 3 days.

The dam was so heavily damaged during the earthquake that it could not be repaired to safely hold its water supply during another large earthquake. A replacement dam was needed—one designed to withstand strong ground shaking associated with earthquakes expected in the area. In studying records of strong shaking from the 1971 shock and other shocks, USGS scientists realized that shaking near the epicenter of an earthquake is much stronger than had been recognized prior to 1971. Hence, they recommended the new dam be designed to withstand shaking about three times stronger than that assumed in earlier design studies. The recommendations were met with skepticism at first, because critical structures were being designed for lower levels of shaking at that time. Inasmuch as the new dam was to be financed with Federal disaster assistance funds, the higher estimates of shaking were used in its design.

The new 33 million-dollar Los Angeles Dam and Reservoir, located about 1 kilometer up the valley from the old Lower San Fernando Dam, was built in 1975-76. However, the Lower San Fernando Dam was not dismantled. Instead, it was reconstructed—though not to meet the USGS shaking estimates—to provide a holding basin for storm water and to back up the new dam.

Two decades later, the 1994 Northridge earthquake put the Los Angeles Dam to the test. The Northridge earthquake was approximately equal in magnitude to the San Fernando event. Ground shaking was very strong, with amplitudes among the highest ever recorded but consistent with the USGS estimates. Yet the dam showed only minor deformation and superficial cracking. Despite the intense shaking, the crest of the dam moved only 2.5 centimeters sideways and settled only 9 centimeters. In contrast, the Lower San Fernando Dam again suffered heavy damage. Had the old dam been holding as much water as it had in 1971, the damage would have been far greater—at least equaling that from the 1971 earthquake.

This success story focuses on dams. However, other critical structures—such as nuclear power-plants, bridges, and hospitals—are being built more strongly today to resist the violent shaking that is now recognized to accompany large earthquakes.

Communicating and Applying What We Have Learned

Communicating the scientific findings of the USGS and applying those findings to meaningful seismic-hazards reduction are multifaceted and long-term efforts. Communicating the results ranges, for example, from providing raw data to researchers via the Internet to distributing highly interpreted seismic concepts to the general public. Applying the lessons learned from the earthquake ranges from changing laws and building codes to initiating long-term research and instrumentation programs in anticipation of future events. Some of these activities can be systematically planned and executed; others are highly experimental and must rely on *ad hoc* decisions and windows of opportunity for successful implementation. The USGS, however, has anticipated many communication and application needs of society, and has practiced and established its role in this regard since the inception of the National Earthquake Hazards Reduction Program (NEHRP) in 1977. The evolution of this role to date is partly encapsulated in this section through several examples of current communication and application techniques used by the USGS. ◆

This Report

This report is part of a multimedia approach for reporting USGS findings on the Northridge earthquake. The USGS processed in parallel (1) this printed document, (2) a replication of this document in electronic format, and (3) a hyperlinked Hypertext Markup Language (HTML) tour of USGS and related findings beginning at the Northridge Earthquake Home Page on the World Wide Web (WWW) (see p. 8). This multiphased, interconnected approach serves many functions which allow for a variety of views and levels of detail for readers with widely disparate interests and levels of scientific understanding.

The electronic copy of this report is contained in several Adobe Portable Document Format (PDF) files. These files contain all text and illustrations seen in the printed report, and may be downloaded and printed using commonly accessible Internet protocols as well as viewed using Adobe Acrobat reader software. The PDF files are readily accessible through links from the Northridge Earthquake Home Page on the WWW.

The HTML tour of the Northridge earthquake investigations and findings is based on the outline of the printed report, yet the tour is not a linear process. An investigator may immediately link into any chapter or topical area from the Northridge Earthquake Home Page. The HTML tour also provides links to scientific documents such as articles for scientific journals, reference lists, fact sheets, and other materials that formed the basis for this project. Additionally, the HTML tour provides many links to earthquake-related topics beyond the scope of the Northridge earthquake project. The HTML tour is a "living" entity that will be updated and modified continually by the USGS as new information becomes available, or as obsolete materials are deleted. ◆

Access this report via the WWW at: **http://geohazards.cr.usgs.gov**

Upgrading the Seismic Instrumentation Network

A major function of the USGS is to provide earthquake information quickly to other government agencies, emergency response organizations, utility companies, transportation entities, and others immediately affected by earthquakes. The USGS and Caltech have substantially improved seismic recording in southern California, and they have developed a program for continuing to upgrade the system to improve its reliability and speed of data transmission. Specific goals of the instrumentation program are:

- Recording and distributing ground-shaking information in near real time (within a few minutes of detection of shaking) that can be used for estimating the extent and distribution of the resultant damages (see p. 72).
- Maintaining the traditional functions of a strong-motion network; that is, onsite recording of strong shaking (up to 2*g*) in the event of a telemetry failure.
- Ensuring that the analysis system and telemetry are easily extended to include additional sensors, and are able to readily interface with other regional seismic networks.
- Ensuring that the network remains functional in the event of single-station failure.
- Developing a pilot program on very rapid information transmission that can be used for early warning of strong shaking.

The instrumentation program received startup funding through the NEHRP agreement (see p. 4). Other funding sources include Pacific Bell Telephone for assistance in developing a telemetry system; the California OES through a proposal by Caltech and the CDMG; the NSF through a proposal by Caltech, and private funds raised by Caltech. ◆

A USGS scientist kneels beside a portable seismograph station during the Northridge earthquake aftershock study. The site is a parking lot in front of the collapsed parking garage at California State University, Northridge.

Continuous GPS Monitoring

A consortium of agencies (SCEC, USGS, and NASA) is currently installing a network of continuously recording Global Positioning System (GPS) instruments throughout southern California. The network, named the Southern California Integrated GPS Network (SCIGN), provides rapid, continuous measurements of ground deformation. As of April 1996, 38 stations were established, and there are plans for 30 more to be placed by the end of the year. Data have been collected from several stations that began operation in late summer 1994, and so far data quality has been excellent. The data are processed at the Scripps Orbit and Permanent Array Center (SOPAC) in La Jolla and the Jet Propulsion Laboratory (JPL) in Pasadena primarily through funding by the USGS, NSF, and NASA.

Continuously recorded GPS data have provided a new baseline for studying compression of the Earth's crust across southern California. Displacements due to compression may prove to be indicators of stress accumulation on blind thrust faults similar to the fault that ruptured in the Northridge earthquake.

All of the current and archived GPS raw data from the network are available through several anonymous FTP (file-transfer protocol) sites on the Internet (see p. 8). The most recent results of the continuously operating GPS array are analyzed by the USGS and researchers at SOPAC and JPL. ◆

GPS results may be viewed on any of several sites on the WWW that may be accessed through the following Uniform Resource Locator (URL): **http://scec/gps.caltech.edu/scign.html**

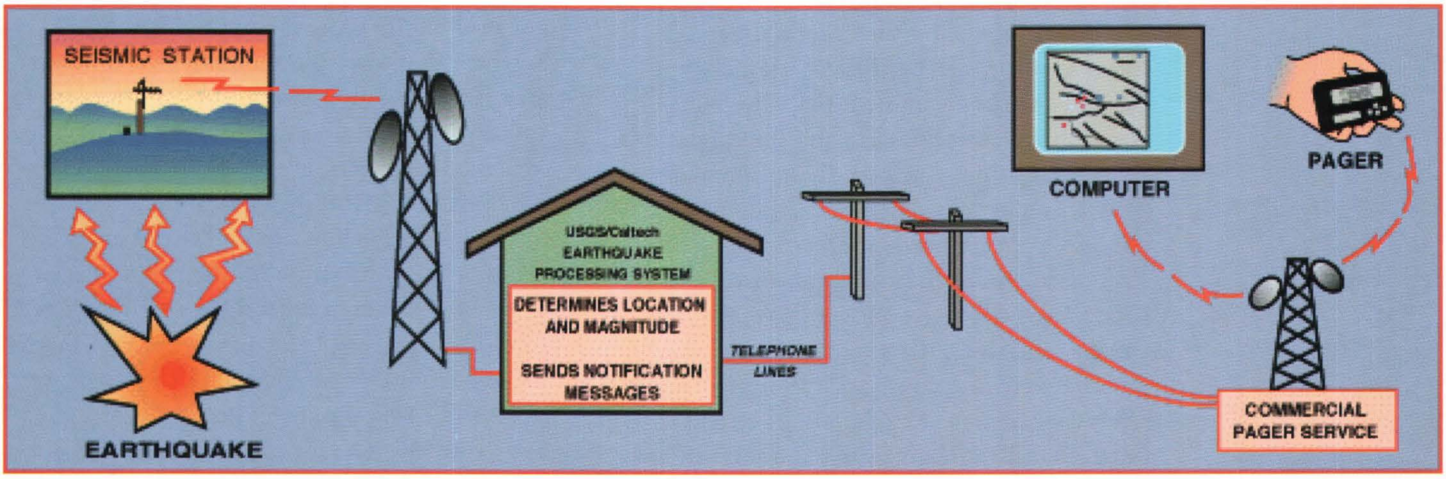
Speeding Earthquake Disaster Relief Using CUBE (Caltech/USGS Broadcast of Earthquakes)

Scientists and engineers from the USGS and other institutions and agencies aided emergency managers by preparing a shaking-intensity map for the Los Angeles area (see p. 55). This map showed estimated severity of shaking and the levels of damage likely associated with such shaking. This map was available long before a complete picture of the damage could be assembled, and it enabled emergency managers to promptly locate the hardest hit areas and to send appropriate help. The shaking-intensity map was the first use of such a map to help focus relief efforts during a disaster.

To quickly prepare accurate shaking-intensity maps after an earthquake, essential information about the location, size, and nature of the earthquake was compiled. A comprehensive broadcast system for reporting this essential information was established in 1991 in southern California. The broadcast system, called CUBE, automatically reports earthquakes recorded by the 350-station southern California seismograph network operated by the USGS and Caltech. (A companion seismograph network and broadcast system reports earthquakes in northern California; similar networks are located in other earthquake-prone areas of the United States.)

Whenever a sizable earthquake strikes, designated scientists are notified via telephone pager.

Subscribers to the CUBE system, such as railroad companies, utility companies, and television stations, are also simultaneously notified. Instead of a telephone number, the location, size, depth, and other information about the earthquake scroll across the pager display. This information is fed into a computer-modeling system that incorporates geological conditions of an area. Scientists use the modeling system to calculate the shaking intensity for different locales within a large area surrounding the earthquake's epicenter. Thus, rapid, reliable information from seismograph networks, until recently used primarily for research, is proving its value during earthquake disaster-relief operations. ◆



These are the basic elements of the broadcast system that transmits information about earthquakes in southern and northern California. Energy from earthquakes is recorded at numerous field stations on instruments called seismographs. These seismic signals are relayed nearly instantaneously from this seismograph network to analysis centers at Caltech in Pasadena and at the USGS in Menlo Park. From these centers, earthquake information including time, location, and magnitude is relayed to designated scientists and to system subscribers via pager within 1 or 2 minutes of an earthquake. The information can also be displayed as a map on a personal computer.

Special Publications—Magazines and Fact Sheets

During 1994-96, the USGS produced several specialty documents related to the Northridge earthquake. These included two issues of the USGS magazine ***Earthquakes & Volcanoes*** devoted entirely to early findings about the earthquake, and several fact sheets in the series ***Reducing Earthquake Losses Throughout the United States.*** Printed copies of Earthquakes & Volcanoes, v. 25, nos. 1-2, 1994, and the fact sheet series (1995-96) may be obtained from the USGS using the following contact:

USGS Information Services
Box 25286, Building 810
Denver Federal Center
Denver, CO 80225-0046 USA
Tel: 303-202-4200
URL: **http://www.usgs.gov** ◆

The fact sheet series is also available on the WWW at the following URL: **http://quake.wr.usgs.gov**

The Southern California Earthquake Center (SCEC) Knowledge Transfer Program

The USGS actively supports and collaborates with SCEC (see p. 7) in its scientific and knowledge-transfer functions through membership on SCEC's Board of Directors. SCEC's Knowledge Transfer Program, funded by the Federal Emergency Management Agency (FEMA), targets end users—the people and entities who make ultimate use of scientific data and interpretations. Specifically, these include disaster preparedness officials, practicing engineering design professionals, policy makers, southern California business communities and industries, local, State and Federal government agencies, the media, and the general public. Knowledge-transfer activities consist of forums and workshops, discussions among groups of end users and scientists, documenting and publishing these interactions, and developing products compatible with user needs. In 1994, the SCEC Board of Directors endorsed the concept for a Research Utilization Planning Process that focused on full scientific participation throughout the process and in implementing the plan. The process distinguished the end users that should be targeted for product development from the end users who need information, but not in the form of specialty products. SCEC is now working toward producing several reports for specific end-user groups such as property and casualty insurance underwriters, civil and structural engineers, engineering geologists, urban planners, and the general public. Examples of collaborative knowledge transfer between the USGS and SCEC include the handbook ***Putting Down Roots in Earthquake Country*** (described below), and the ***Los Angeles Region Seismic Experiment (LARSE)*** (see p. 19). The very nature and contents of these two ventures—one for the general public, one for scientific researchers—clearly illustrates the breadth of communications achievable by the USGS and its collaborators. ◆

Putting Down Roots in Earthquake County can be inspected on the WWW at: **http://scec.gps.caltech.edu/roots/roothome.html**

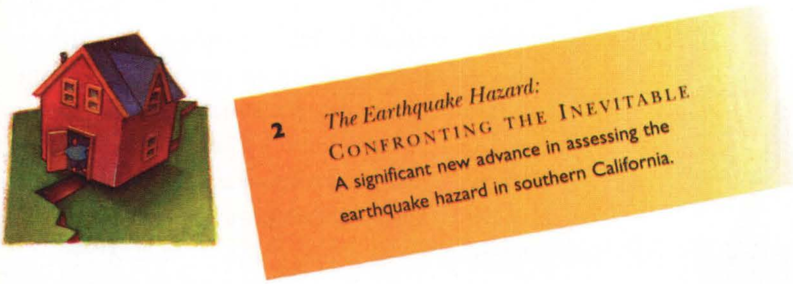
Results from The Los Angeles Region Seismic Experiment (LARSE) are frequently updated on the WWW at: **http://scec.gps.caltech.edu/larse.html**

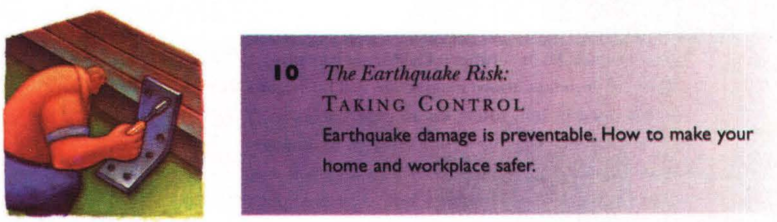
Putting Down Roots in Earthquake Country—
A Personal Handbook for Earthquake Safety

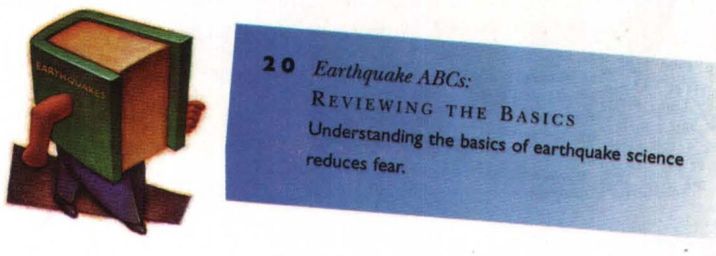
Part of the USGS effort to reach out to citizens is a 32-page personal handbook that was distributed through public libraries in southern California in October 1995. This handbook encourages earthquake awareness and preparedness by helping people understand the hazards we all face and what can be done about them. Many people in southern California and elsewhere do not take measures to prepare themselves for earthquakes for a variety of reasons, including fear, denial, and ignorance. We avoid thinking about the things that frighten us; we deny that rare events will affect us; and in many cases, we simply do not know what we can do to help ourselves.

The new handbook ***Putting Down Roots in Earthquake Country*** speaks to our fear, denial, and ignorance in three parts:

- *The Earthquake Hazard*—Confronting the Inevitable: How concerned should we be about earthquakes? The handbook tells us what we can expect from the earthquake threat while we live in southern California.
- *The Earthquake Risk*—Taking Control: Earthquakes are inevitable, but the damage from earthquakes is not. We can take control of our environment to make our homes and workplaces safer. The handbook clearly illustrates what individuals can do before, during, and immediately following an earthquake.
- *Earthquake ABC's*—Reviewing the Basics: Understanding reduces fear, and earthquakes and their effects are understandable. The handbook offers clear explanations of earthquake science.





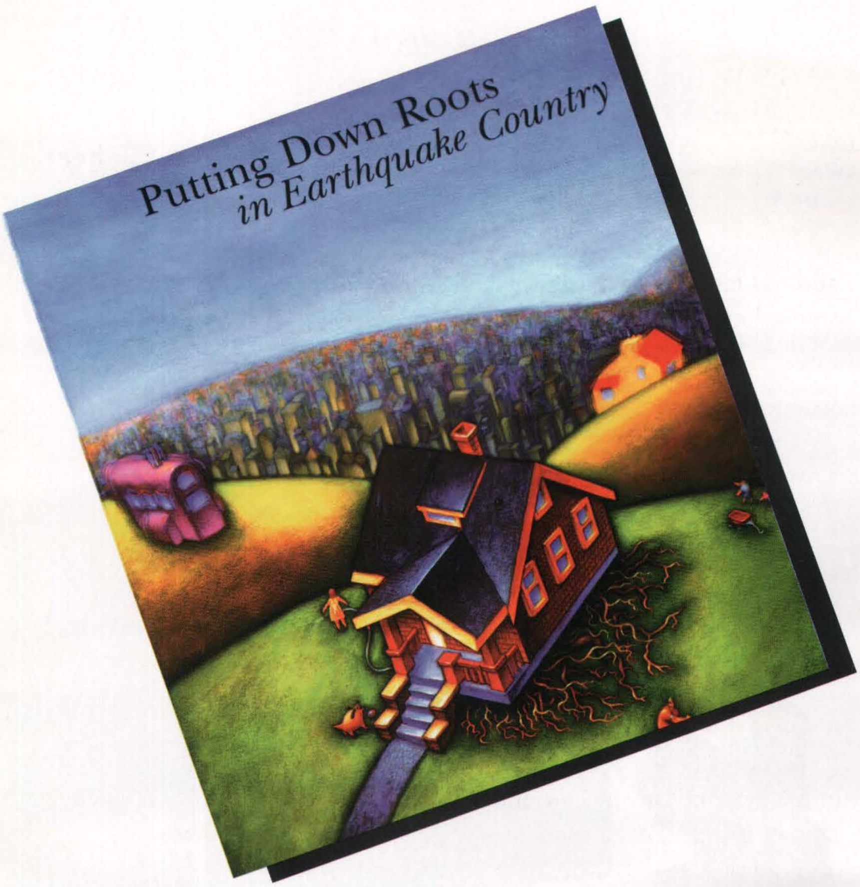


The handbook is a clearly written, profusely illustrated document carefully designed for easy reading and frequent reference. The many practical aspects of the handbook include an outline for an eight-step family earthquake plan and suggestions for training family members in earthquake safety.

The handbook was prepared and brought to southern Californians by the USGS, the National Science Foundation Southern California Earthquake Center, the California Governor's Office of Emergency Services, the Federal Emergency Management Agency, the American Red Cross, and other concerned businesses and organizations of southern California. Two million copies of the handbook were distributed in October 1995 to schools, companies, and the public through public libraries and the SCEC Knowledge Transfer Office. ◆

From the Handbook...

"The road to earthquake safety"



"We would all be better prepared for earthquakes if we knew when the next one was coming. However, unlike the storm front that must travel to you before rain can begin, there are no warning signs for earthquakes. We have found no scientifically verifiable way to predict earthquakes."

"Even though we cannot predict the time of the next earthquake, science can help us live safely with earthquakes. The road to earthquake safety follows several steps. First, we must estimate what earthquakes of what size are likely to occur (geology). Given that earthquake, we then estimate what the shaking will be (seismology). Given that shaking, we estimate the response of different types of buildings (earthquake engineering). Only with all these steps completed can we take the steps as a society to enact building codes and retrofitting programs to make our community safer." ◆

Updating California's Earthquake Hazards Reduction Program

The State of California, through its Seismic Safety Commission, began a series of 5-year plans for the California Earthquake Hazards Reduction Program in 1986. The report *California at Risk* details the plans and is updated annually to reflect new information and changing needs. The USGS contributes to the State program through membership on and liaison to the California Seismic Safety Commission, through participating regularly in updating the State report and by membership on FEMA's post-disaster assessment teams whose recommendations are incorporated into State plans. As part of the response to the Northridge earthquake, the USGS participated on an interagency team that developed the 1994 post-earthquake update to *California at Risk*. This update, originally published separately as a 1994 Status Report will be fully integrated into the State Plan in late 1996. *California at Risk* is an excellent example of the link between scientific findings and applying those findings to earthquake-hazards reduction through updating building codes and changing and enacting legislation. ◆

Conclusions—Working Toward National Seismic Safety

Despite the injuries, loss of lives, and economic setbacks caused by the Northridge earthquake, there were many successes in the way the Los Angeles region withstood the event. Because of the awareness of earthquake hazards in southern California, tens of thousands of buildings did not collapse and the number of casualties was relatively low. The fortuitous early morning occurrence of the earthquake, when few people were on the freeways and in large structures, was another significant life-saving factor. Compared with earthquake impacts in other parts of the world, losses from the Northridge quake (especially deaths and injuries) were remarkably small for a region where millions of people live.

Ongoing research by the USGS and other NEHRP agencies continues to improve our understanding and awareness of earthquakes, and has resulted in substantive measures to strengthen our cities against damaging earthquakes. Lessons learned from the 1971 San Fernando earthquake helped to reduce damage from the Northridge earthquake. The studies of damage and ground motions from the Northridge earthquake show that a modern California urban area can be broadly resilient although locally vulnerable to the widespread shaking from a moderate earthquake.

However, many of our successes were found in areas of "moderate" shaking. Some of the important results from studies of this earthquake show that cities will suffer heavy damage in the areas of "strong" ground shaking. We saw that an earthquake of moderate size can produce intense ground motions in the immediate vicinity of the fault rupture. During the

Northridge earthquake, the areas of strong shaking were relatively small and limited mainly to a few areas in the San Fernando Valley and the unpopulated mountains to the north. Southern Californians may not be so lucky in the next event. Another earthquake of similar magnitude could focus the strong shaking directly at a densely populated region, or the next earthquake could simply be larger with damage spread over a much greater area.

We are certain that more earthquakes will occur. The next moderate-to-strong damaging earthquake to affect our country may hit Los Angeles again, or it could happen in San Francisco, Seattle, Memphis, Boston, or many other urban areas that sit close to potentially active faults. In any of these regions, we can expect economic losses to be in the range of tens to hundreds of billions of dollars, with human casualties depending upon the seismic resistance built into the particular environment. In areas that are substantially less prepared than southern California, the losses could approach those witnessed in recent earthquakes in urban areas of other countries, such as Kobe, Japan.

Principal roles of the USGS are to use its scientific expertise to identify and communicate seismic hazards, and to help ensure that our society attends to them. Earthquakes like the Northridge event focus USGS efforts in one region, and scientists are able in a short time to greatly increase the base of knowledge about earthquakes with intensive post-earthquake studies. In the aftermath of an earthquake we see dramatically the successes and failures of our efforts.

The successes of the USGS response to the Northridge earthquake are many, and are exemplified by those discoveries that helped change the way we now look at earthquakes. From applying seismic recording networks to immediate disaster response to devising predictive models of the effects of future earthquakes, the USGS and its cooperators have helped create a prototype that bears review throughout the Nation.

However, the post-earthquake studies are only a small part of ongoing programs to reduce seismic hazards. It is during the years between damaging earthquakes that most of the work is done. Understanding and identifying earthquake hazards and setting the stage for mitigating them is a continuous process that transcends the immediacy of public attention to disastrous events.

Wide-ranging efforts—from studying the fundamentals of earthquake physics to developing applied products such as probabilistic seismic-hazards maps—all contribute to a comprehensive USGS program committed to reducing earthquake losses. ◆

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